

MAXIMIZING QIVIUT GROWTH IN MUSKOXEN

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MAXIMIZING QIVIUT GROWTH IN MUSKOXEN

A
THESIS

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By
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Abstract

Qiviut, the insulating underwool grown annually by muskoxen, is the basis of a successful knitting industry in Alaska. This study tested the hypothesis that the dietary sulfur-amino acid methionine could limit qiviut growth. Effects of commercial rumen-protected methionine supplements were measured in three experiments. In Experiment 1, emergent qiviut growth began in May and June, peaked in August and declined substantially by October. Three commercial methionine supplements were palatable and promoted fiber growth in subadult and adult muskoxen. In Experiment 2, the methionine supplement Smartamine promoted qiviut quality, growth, annual yield and strength. In a commercial enterprise, Experiment 3, Smartamine stimulated qiviut yield. For lactating muskoxen, qiviut responses were independent of nutrition, whereas effects on body weight and protein deposition were confined to females on a low plane of nutrition. It was concluded that addition of rumen-protected methionine to diets of farmed muskoxen can effectively promote qiviut production.

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Introduction

Muskoxen are one of only two ungulate species that currently inhabit the circumpolar arctic (White et al., 1981; Klein, 1992). An important and striking adaptation of the muskox to the arctic environment is its thick, multi-layered pelage. The outer pelage layer consists of long, dark brown permanent guard hairs, beneath which lies a dense coat of soft gray-brown underwool, known by the Eskimo name, qiviut. Qiviut fibers begin growth from secondary follicles in early spring, completing the majority of growth by late October (Flood et al., 1989), to reach a depth of 4 to 8 cm on the body's core by late autumn (Von Bergen, 1932; Wilkinson, 1975).

Seasonal changes in insulation enable terrestrial mammals to minimize heat loss in winter (Scholander et al., 1950; Feist and White, 1989). In muskoxen, the combination of high secondary follicle densities and depth of the underwool indicate that the winter pelage has an extremely high insulative capacity. As a result, the lower critical temperature of adult muskoxen, defined as the point at which the animal must increase metabolic rate to counteract heat loss, is estimated to be less than -30°C (Scholander et al., 1950; Nilssen et al., 1984). Thus selection in winter appears to be for a high whole body insulation which allows muskoxen to minimize heat loss and better maintain energy balance when forage availability is seasonally limited (White 1975; White et al., 1981).

Qiviut is shed, or molted, annually in April-May preceding warm temperatures of summer. The molting process is highly synchronized, initiated by renewed activity of winter- dormant secondary hair follicles (Flood et al., 1989). In Alaska, qiviut is

collected from captive muskoxen during the spring shed, supporting a successful cottage knitting industry (Bruce and Robertson, 1994). Knitted items are in demand and the market price is high. Because of the high market value of qiviut, muskoxen have been tamed and raised on farms as fiber-producing animals (Wilkinson and Teal, 1984).

Commercial farming of muskoxen is a relatively new endeavor (Wilkinson and Teal, 1984), and studies have yet to determine the role of diet on qiviut production. Furthermore, seasonal rates of fiber growth, and how these might differ with sex and age, have not been described. In domestic sheep and goats, dietary supplementation with rumen-protected methionine has been shown to enhance fiber growth (Reis, 1988; Russel, 1992; Reis and Sahlu, 1994; Qi and Lupton, 1994), particularly when there is a limitation in dietary protein (Cottle, 1988; Pickering and Reis, 1993; Mata et al., 1995). Methionine is considered the preferred dietary precursor for wool protein synthesis, increasing both fiber length and fiber diameter in sheep (Reis, 1979, 1988). Following absorption in the small intestine, methionine is converted to cystine in the body by transulfuration. Cystine is critical to wool synthesis because it provides disulfide bonds, or cross-linkages, that are required for fiber formation. Keratin, the primary component of wool and hair, is known to have a high concentration of cystine when compared to most other body proteins (Robbins, 1993). Ruminal microorganisms can degrade dietary methionine, which constitutes a major limitation to the supply of methionine, and cystine, for wool growth. Protection of dietary methionine from microbial degradation can be achieved by a chemical protectant, and some cystine and methionine containing proteins are naturally resistant to ruminal degradation (e.g., fish and blood meal). Commercially

available rumen-protected methionine and fishmeal can positively influence protein deposition in members of the family Bovidae (e.g. cattle, sheep, goats) when the post-ruminal supply is limiting (Papadopoulos et al., 1984; Oke et al., 1986; Klemesrud, 2000). The ability of methionine supplements to improve wool production and body protein turnover in domestic ruminants suggests that such positive gains could be made in farmed muskoxen.

A second factor determining if sulfur amino acid availability could affect qiviut and hair growth is whether the quantity of qiviut needed to meet whole body requirements for insulation is high relative to that required for other productive purposes. In fact, the pelage of muskoxen represents a substantial investment of protein. Adamczewski et al. (1995) determined that hair mass, or pelage, constitutes 4.5 % of the ingesta-free body mass (IFBM) of adult females. Further, they calculated that cows containing 20 kg of protein in IFBM had 5 to 5.5 kg of additional protein in the pelage, which has a high sulfur-amino acid content relative to the lean body mass. Of the pelage mass, approximately half (2.5-3.0 kg) represents annual qiviut growth (White et al., 1991). Muskoxen produce qiviut from May to November (Flood et al., 1989), coinciding with periods of rapid growth in young animals and lactation in females (Thing et al., 1987; White et al., 1989). Although peak and post-peak periods of plant production support these functions, because of the possibility of ruminal degradation and competing demands for body protein and milk synthesis, methionine could become limiting during the wool growth season. This would be especially likely to occur in animals fed lower quality diets. The aim of these experiments was to establish rate and extent of qiviut

growth in captive muskoxen, and secondly, to evaluate the efficacy of supplementing muskox diets with rumen-protected methionine.

Experimental trials were conducted at the Large Animal Research Station at the University of Alaska Fairbanks (AK) and a field trial was conducted at the Musk-Ox Development Corporation (MODC) Commercial Facility, The Musk-Ox Farm, in Palmer (AK) to evaluate the effects of supplementing muskox diets with rumen-protected sulfur-amino acids. Chapter 1 describes two experiments, the first of which addressed seasonal rates of qiviut growth and palatability of three commercially available dietary supplements of methionine. Qiviut growth was measured over the course of the wool growth season (May 1 - Nov 1), to assess patterns of seasonal growth and supplement effect. In addition to describing seasonal patterns of qiviut growth, patterns of fiber growth, shed and emergence with respect to diet and age were also evaluated. In the second experiment qiviut production, body weight gain and hoof growth (an estimate of protein deposition) was measured throughout the wool growth season in lactating females on either a high (HP) or low (LP) plane of nutrition. Animals received no supplement in the first season, and Smartamine M methionine supplements were fed in the second year of the study. Techniques were developed to assess rates of wool growth, and the chapter presents evidence for seasonal partitioning of methionine between qiviut growth, protein deposition and body weight regain in female muskoxen.

Chapter 2 describes the results of a study conducted at the MODC in which the efficacy of using the rumen-protected methionine supplement Smartamine M, was assessed in a commercial enterprise. Having established that the Smartamine supplement

was palatable to muskoxen, and that it effectively increased qiviut yields in an experimental setting, this applied study was conducted on mature steers fed a high protein pelleted ration with and without Smartamine M methionine. No modifications were made to the communal feeding regime. Combed qiviut yields and body weights were compared between supplemented and non-supplemented steers. While acknowledging that results are preliminary due to limitations of animal numbers, it was found that Smartamine stimulated qiviut growth after accounting for between year effects. Also discussed in Chapter 2 is the effect of methionine on steers in comparison to growing or lactating muskoxen. The Chapter addresses costs and benefits of feeding rumen-protected methionine supplements in this commercial establishment. It is argued that the cost effectiveness of Smartamine M, and other commercial preparations that could be incorporated into commercial rations, is high even with high quality feeds. As a supplement to a low quality, inexpensive ration, methionine would be important in a commercial muskoxen enterprise for stimulating the growth of young animals as well as for maximizing qiviut yield in all animals.

Chapter 1.

Effects of methionine supplements on wool (qiviut) growth, live weight gain and protein deposition in captive muskoxen¹

Introduction

The muskox, a medium-sized arctic ruminant, produces a thick, multi-layered pelage, which effectively insulates it through eight-plus months of arctic winter. The outer pelage layer consists of long, dark brown permanent guard hairs that form the animal's characteristic 'skirt.' Beneath the guard hair is a dense coat of soft gray-brown underwool, called qiviut (Bruce and Robertson, 1994). In Alaska, muskoxen have been farmed for this underwool since the 1960s (Wilkinson and Teal, 1984).

In early spring, qiviut fibers grow from secondary follicles, completing the majority of growth by November. The secondary follicles remain dormant throughout

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winter until renewed activity in April precipitates synchronized shedding of qiviut over a short period of time (Flood et al., 1989). Qiviut has a reported average fiber diameter of 10 to 16 μm , a fiber length of 4 to 8 cm (Von Bergen, 1932; Wilkinson, 1975), and an average scoured yield of 93.3% (Reed, 1983). These characteristics place qiviut in the category of super-fine fibers, valued for the production of extremely fine, soft yarn.

An extensive literature exists on the regulation of fiber production in domestic sheep and goats (Russel, 1992; Sumner and Bigham, 1993; Reis and Sahlu, 1994), which should be directly applicable to qiviut growth by muskoxen. For ruminants, the dietary supply of sulfur-containing amino acids (S-AAs) can be limiting (Storm and Ørskov, 1984). Methionine is considered the preferred precursor for wool protein synthesis (Reis, 1979; 1988), and can enhance wool growth and live weight (LW) gains, particularly when there is a limitation in dietary protein (Pickering and Reis, 1993; Mata et al., 1997). Chemically protecting methionine against microbial action in the rumen increases available methionine for absorption in the small intestines (Ferguson, 1975), a process known as ruminal bypass. Commercial forms of rumen-protected methionine (RPMet) are available, as well as fishmeal, a source of S-AAs that is naturally resistant to microbial degradation.

The aims of the first experiment were to assess the palatability and effect of supplemental sources of RPMet fed to muskoxen, and to determine seasonal patterns of qiviut growth. The second experiment was designed to examine the effects of plane of nutrition in qiviut growth, and to measure effects of one RPMet supplement on raw fleece

weights, qiviut growth rates, fiber characteristics, rates of protein deposition and live weight gains in female muskoxen.

Methods

All experimental procedures were approved by the Animal Care and Use Committee of the University of Alaska Fairbanks (UAF) (protocol number 94-06). The study site was the Large Animal Research Station (LARS) located at UAF (64° 49' N, 147° 43' W). Muskoxen were maintained in outdoor pens year-round, and had access to fresh water in summer months, and loosely-packed snow in winter. Before initiating trials, animals were treated with an antihelmetic (Levamisole), according to UAF Veterinary Services protocol.

Experiment 1: Palatability of Methionine Supplements and Seasonal Patterns of Qiviut Growth

Sixteen muskoxen of mixed age and sex were assigned to four dietary treatments in a randomized block design. Each treatment contained one lactating adult female, one adult steer, one two-year old and one yearling. Animals grazed seasonally available brome pasture, and were given *ad libitum* access to brome hay year-round and a high protein pelleted ration fed at a rate of 29 g/kg LW^{0.75} three times per wk (Table 1). From May 21 to October 31, each group's pelleted rations included either no supplement

(CON), Mepron M85 (MEP) (Degussa Corp., Ridgfield Park, NJ), Smartamine M (SMA) (Rhone-Poulenc, Atlanta, GA), or Sealac menhaden fishmeal (FM) (Zapata Protein, Hammond, LA). MEP and SMA supplements were top dressed onto the ration three times a week, giving a daily rate of $68.3 \text{ mg/kg LW}^{.75}$, while FM supplement was pelleted into the ration providing the fishmeal supplement at a daily rate of $1.92 \text{ g/kg LW}^{.75}$. MEP, SMA and FM supplements provided methionine at a daily rate of 46 mg, 46 mg and 43 mg/kg $\text{LW}^{.75}$ respectively. When fishmeal was included in the diet, the pelleted ration was fed at 76% ($22 \text{ g/kg LW}^{.75}$) to maintain isonitrogenous diets.

Muskoxen were acclimated to diets for 21 d prior to experimental trials. In a preliminary feed preference trial immediately preceding the 21-d acclimation period, six juvenile muskoxen had consistently selected against the FM diet, while demonstrating no preferences between the remaining three diets (SMA, MEP or CON). To accommodate for potentially low palatability, the FM diet was introduced at 25% at the onset of the acclimation period, and increased by 25% weekly.

Through the course of the experimental trial, animals were grouped by age class (four muskoxen per pen), and groups were rotated through six pens to maintain optimal grazing conditions. Three times per wk at 0900, animals were penned individually and fed diets. To assess palatability, records were kept on the amount of feed offered and refused. All animals were weighed weekly, and feeding rates were updated according to LW.

Rate of giviut growth ($\text{mg/cm}^2/\text{d}$) was measured by clipping $5 \times 5 \text{ cm}^2$ patches established on the shoulder, mid-side and rump of each animal. Patches were clipped to

the skin level on d 0 and again on d 21 using small animal clippers (Oster, no. 30 blade) in June, August and October.

Clipped samples collected in June were not processed because initiation of qiviut growth was not evident in many animals at the onset of data collection (June 7). Instead, relative abundance of qiviut in the 21-d samples was ranked on an integer scale from 1 to 6. A rank of "1" corresponded to no qiviut in the sample, while a rank of "6" indicated levels of wool growth similar to that seen in a period of peak growth (August). Fiber samples were oven dried at 40° C for 24 h, and weighed from a dessicator. From within each clipped sample, three subsamples were collected and weighed. Guard hair and qiviut were separated using a Canon imager, subsamples were oven dried at 40° C for 24 h, and raw qiviut weight was recorded. Qiviut was defined as fibers < 40 μm based on representative samples of commercially cleaned muskox underwool. Average percent qiviut from three subsamples was used to calculate the weight of total guard hair and qiviut, expressed as $\text{mg}/\text{cm}^2/\text{d}$.

Qiviut is harvested annually from captive muskoxen by combing it off animals during the spring shedding season (White et al., 1991; Groves, 1992). In the spring following the feed trial (1997), experimental animals were completely combed, and raw fleece weight (kg) was recorded. Raw fleece weight refers to the total qiviut yield from an animal, measured immediately after combing. Qiviut is commercially sold by raw weight, then batched for commercial cleaning and processing; consequently, clean fleece weights are not available. In order to accommodate for differences in age and body size, total fleece weight was expressed as $\text{g}/\text{kg LW}$.

Experiment 2: Plane of Nutrition and Methionine Supplementation

Between May 1, 1996 and October 31, 1997, nine adult female muskoxen were allocated to two treatment groups. All animals were given *ad libitum* access to brome hay and seasonal grazing. One group of females was maintained on a high plane of nutrition (HP: $n = 5$), receiving the high protein pelleted ration (Textured Ration, described in Exp. 1) either two or three times weekly, at a daily rate of $12.5 \text{ g/kg LW}^{.75}$. The other group was kept on a low plane of nutrition (LP: $n = 4$), receiving no pelleted ration. The HP/ LP treatment was initially established in 1987 (White et al., 1989), and had been maintained year-round through the beginning of the experiment. Female calves were reared on the same treatment as their dams, and were recruited into the treatment group at 2.5 yr. (White et al., 1997). Complete details of the diets are reported in White et al. (1989).

In year 1 of the experiment (1996), wool growth and live weight were measured in the five HP and four LP lactating females. Hoof growth was measured in three HP and three LP animals, and used as an index of protein deposition. These data provided a control for the supplement treatments applied in the next year. In year 2 (1997), HP and LP muskoxen received rumen-protected methionine (SMA) from May 1 to October 31 at a daily rate of $68.3 \text{ mg/kg LW}^{.75}$. The methionine supplement was top-dressed onto the pelleted rations of HP animals. LP animals were given the supplement mixed into 75 g whole grain barley and 75 g pelleted ration. Supplemented rations were offered three

times per wk at 0900, and animals were penned individually while consuming rations. Feeding rates were updated weekly according to measures of live weight. In year 1, HP and LP groups were maintained on separate pastures offering similar grazing opportunities, while in year 2, animals grazed a common pasture to facilitate feeding routines.

LW (kg) was measured weekly. Rate of qiviut growth ($\text{mg}/\text{cm}^2/\text{d}$) and raw fleece yields (kg) were collected as described in Exp. 1. In addition to d-21 samples, clipped samples were collected on d 7 and d 14 from adjacent $5 \times 5 \text{ cm}^2$ patches. Location of patches was assigned randomly within areas (approximately 160 cm^2) on the shoulder, mid-side and rump. Qiviut growth rates were compared between d-7, d-14 and d-21 samples to determine whether or not clipping qiviut to the skin surface resulted in compensatory growth.

Linear qiviut growth (mm/d) was measured using a modified version of the dyeband technique (Chapman and Wheeler, 1963). Dyebands were established adjacent to the clipped shoulder patch and applied every six weeks from June 25 to October 31. Qiviut and hair fibers were dyed at the skin level using a mixture of 50% black hair dye (Matrix Essentials) and 50% hydrogen peroxide. Dyebands were harvested on December 12 using small animal clippers (Oster, 40 blade). Measurements of qiviut linear growth and staple length were made on relaxed groups of fibers.

Average fiber diameter (AFD), standard deviation (SD) and coefficient of variation (CV) were determined using qiviut combed from the shoulder opposite to the clipped patch. Samples were analyzed at the Wool and Mohair Research Laboratory at

Texas A & M University, San Angelo, TX using an Optical Fibre Diameter Analyzer (OFDA, Baxter et al., 1992). Staple strength (N/g) was measured using an Agritest staple breaker on samples combed from the lower neck region.

Individual fibers ($n = 10$) taken from the lower neck region of each animal during spring combing were used to calculate variability in diameter along fibers (within fiber diameter variability, WFDV, %). Representative fibers were mounted onto permanent slides, and fiber lengths were recorded. Fibers were viewed through a light microscope at 400x magnification, and a Javelin SmartCam camera transferred video images to a Power MacIntosh 8100/80AV system using Apple Video Player 2.0. Fiber diameter measurements (μm) were made at ten equally spaced intervals along each fiber on still images using NIH Image program 1.61.1. The mean, minimum and CV of diameter along each fiber were calculated.

Between-Year Effects

Because Exp. 2 took place across two qiviut-growth seasons (May to October, 1996 and 1997), potential between-year differences were monitored. Pelleted rations and hay were sampled through the course of both trials, and sent to Midwest Laboratories Inc., Omaha, NE, for proximate analyses. Although no measures were made for pasture productivity, National Weather Service data for the Fairbanks area was used to compare precipitation, temperature, total snowfall in the previous winter, and the total number of spring days (April 1 to May 31) that the minimum ambient temperature was greater than

0° C. Green-up dates for Fairbanks were reported by Dr. J. H. Anderson (in Thoman and Fathauer, 1998) defined as "the date that leaf buds in birch and aspen open just enough to produce a faint but distinct green flush through the forest canopy." In interior Alaska, this process occurs rapidly enough to assign it to a single date (Thoman and Fathauer, 1998).

Statistical analyses

Data were analyzed using the GLM procedures of SPSS 7.0. Yields from the 3 clipped patches were pooled to estimate overall qiviut growth rate for each animal.

Experiment 1: Palatability of Methionine Supplements and Seasonal Patterns of Qiviut Growth.

Qiviut growth data were analyzed using a repeated measures analysis of variance, with age as blocks and diet as main effects. The model for analysis included age, diet and month, with block x diet as the error term for diets. All month effects were tested against residual error. Raw fleece weight data were analyzed in a two-way factorial arrangement, with age as blocks and diets as main effects, and age x diet as the error term.

Experiment 2: Plane of Nutrition and Methionine Supplementation

Repeated measures analyses of variance were used to test for differences in fiber characteristics, growth rates and yields. The statistical model included main effects of nutritional plane and supplement and the nutritional plane x supplement interaction. Cow within plane was the error term for plane, and the residual served as the error term for all supplement effects. When the F test was significant for main effects, differences within plane were determined using paired samples *t* tests, with the residual serving as the error term. Rates of hoof growth were compared using independent samples *t* tests. Two-way repeated measures of analyses of variance were conducted to evaluate the effects of supplementation over time on LW and qiviut linear growth. When live weight was the dependent variable, the within-subject factors were treatment with two levels (no supplement, supplement) and week with 4 levels (1 wk post-calving, 8 wk, 15 wk and 22 wk). When qiviut linear growth was the dependent variable, within-subject factors were treatment (no supplement, supplement) and week with 4 levels (fiber emergence to wk 14, wk 21, wk 28 and wk 35). The residual was used as the error term for all effects of treatment and week. In post-hoc tests, familywise error rate was controlled through Holm's Sequential Bonferonni approach.

Results

Experiment 1: Palatability of Methionine Supplements and Seasonal Patterns of Qiviut Growth.

On d 1 and d 3 of the pre-trial acclimation period, three muskoxen in the FM group initially refused the diet; however, within 20 minutes, animals attempted the feed and subsequently completed the entire ration. After d 3, muskoxen ate all four diets with no differences in rates of consumption or refusals. The initial negative response to FM appeared to be related to odor, and did not deter muskoxen from rapidly acclimating to the new diet. Over the course of the experimental trial, none of the four diets was ever entirely refused, and partial refusals occurred in less than 1% of feedings per group. Consequently, palatability was considered high for all four diets.

Raw fleece yields (g/kg LW) were higher for muskoxen consuming SMA than CON (Dunnett's test, $P = .014$). Rates of qiviut growth in the SMA group were greater than CON in both August (Dunnett's test, $P = .007$) and October (Dunnett's test, $P = .02$; Table 2). No other differences between diets were significant. When pooled by diet and age, rates of qiviut growth were greater in August than in October (month main effect, $P < .001$).

By June 28, adult females showed more advanced stages of qiviut growth than steers or juveniles ($P < .05$; Figure 1a). No other differences were found between age

classes or dietary treatments in June. In August, rates of qiviut growth in yearlings were greater than all other age classes (2 yr, $P = .003$; steers, $P = .001$; females, $P < .001$). A significant main effect of age was attributable to later qiviut emergence in the yearlings (late-June to early July), followed by augmented rates of qiviut growth ($\text{mg}/\text{cm}^2/\text{d}$) in August (Figure 1b). No significant differences in qiviut growth rates between age classes were observed in October.

Experiment 2: Plane of Nutrition and Methionine Supplementation

Qiviut characteristics and growth rates

No evidence of compensatory qiviut growth was observed in clipped patches of animals with or without SMA supplements. Supplementation with SMA resulted in greater raw fleece weights (kg, g/kg LW) from both HP and LP muskoxen ($P < .05$). AFD, staple strength and staple length increased in both groups, ($P < .05$), while WFDV was reduced ($P < .01$; Table 3). Coefficient of variation of AFD decreased with SMA supplements in the LP group only. Differences in qiviut yields and growth rates between unsupplemented nutritional planes were not significant.

Rates of qiviut growth in August increased with SMA in both HP and LP groups ($P < .01$; Figure 2). However, improvements were greater in LP than in HP, which was reflected in the interaction term (plane x treatment: $P = .059$). As a result, qiviut growth rates in August were similar in HP and LP animals provisioned with SMA supplements.

In October, rates of qiviut growth decreased ($P = .001$), and effects of SMA were measurable only in the LP group ($P = .012$).

Supplementation increased rates of qiviut linear growth in both HP and LP from August through mid- September ($P < .002$; Figure 3). In the LP animals, qiviut linear growth was also greater in the November through mid-December period ($P < .05$).

Live weight and protein deposition

For the unsupplemented animals, post-calving live weight gain (LWG) of HP cows exceeded that of LP cows (Figure 4). Initial post-calving LW was not significantly different. However, HP cows were heavier than LP cows by wk 15 ($P < .05$) and tended to be heavier in wk 22 ($P = .07$). Effects of SMA on post-calving LW was detected in the LP group only ($F = 470$, $P = .034$). At one wk post-calving, lower mean LW was observed in LP animals that received SMA ($t = 8.9$, $P < .05$), while at wk 8 and 15 no differences between supplemented and unsupplemented LP animals were evident. At wk 21, the trend was reversed, with supplemented LP animals having higher mean LW than unsupplemented ($t = 6.3$, $P < .05$). Maximum post-calving LW during experimental trials was attained at the end of October in all groups.

Average rate of hoof growth was lower in LP than HP animals when unsupplemented ($P < .01$) (Table 3). Supplementation led to a 46% mean increase in hoof growth in the LP animals ($P < .05$), resulting in rates of hoof growth equivalent to that of HP animals ($P = .994$).

In both years, all females calved in May. In year 1, one HP cow rejected her calf at d 3, and two LP calves died in mid-August. In year 2, one LP calf was stillborn. Because significance of qiviut and LW analyses did not change when females that lost calves were removed, data were maintained in analyses.

Between-Year Effects

Results are reported in 2-month intervals that correspond to growth and harvest of clipped patches (Table 4). In the two study years, temperatures and precipitation from May to August fell within 1 SD of normal (normal based on mean values from 1968 to 1995), although precipitation levels were low in May and June of 1997 (supplemented year). Total winter snowfall in the 1996/7 winter was 12% greater than in 1995/6, but snowfall values in both years were well within 1 SD of normal values. From April 1 to May 31 1997, six additional days with minimum ambient temperatures $> 0^{\circ}\text{C}$ were followed by an earlier greenup date in 1997 (May 5) than in 1996 (May 12). Nonetheless, greenup fell within 1 SD of the average (avg. May 10; SD 8 d) in both years. In early August, brome grass develops seeds that ripen later in the month, and grasses begin to senesce. By September, CP values of brome grass are 10 to 20% of spring values (Quarberg, 1993), and freezing temperatures and snowfall are common. From September to October, both years were cooler than normal, primarily due to cold temperatures in October months. October temperatures do not affect annual pasture production in interior Alaska because pasture growth declines with cooler temperatures in

late August and is terminated by killing frosts in September. Snowcover is persistent in Fairbanks from October through April.

Nutrient analyses indicated that between-year measures of hay quality were similar between May and September. From October through December 1997, LARS brome hay contained higher CP and lower ADF values when compared to 1996 brome hay.

Discussion

As much as 2 to 3 kg of qiviut down can be combed from adult muskoxen annually (White et al., 1991; Groves, 1992). Demand for the fiber is high, supply is limited, and market prices for raw qiviut can range as high as US\$330 to 385/kg. Commercial muskox farming is a relatively new endeavor, and methods to improve qiviut yields through diet have yet to be intensively examined. In a preliminary study, increasing amounts of current annual growth of native willow (*Salix bebbiana*) fed as a supplement to hay and pelleted ration, were associated with increased qiviut length (Boyd, 1993). However, the present study is the first to experimentally assess the role of diet in qiviut production and to characterize rates of qiviut growth during the active period of secondary follicles.

Experiment 1: Palatability of Methionine Supplements and Seasonal Patterns of Qiviut Growth.

The SMA, MEP and FM supplements used in these trials were chosen because of their availability in North America. All three supplements improved raw fleece yields and rates of qiviut growth above control values with SMA having the greatest effects, followed by MEP and FM. Even though MEP provided methionine at a similar daily rate as SMA, it was not as effective. The efficacy of ruminal protection in commercially available Mepron was not measured in our study. However, work with merino sheep suggests that Mepron may be inadequately protected in the rumen (Mata et al., 1995). Stewart and Masters (1990) reported increases in plasma sulfate in merino ewes, indicating rumen degradation of Mepron to sulfate. In a recent comparison of Smartamine M and Mepron supplements in dairy cattle, Blum et al. (1999) observed greater bioavailability of S-AAs in animals fed Smartamine M compared to Mepron, and measured effects on plasma-free AA other than methionine only with Smartamine M supplements. Results from our experiment indicate superior efficacy of Smartamine M in captive muskoxen.

Fishmeal was the least effective of the supplement groups, which was unexpected since it is high in essential AAs, particularly lysine and S-AAs. Fishmeal can effectively improve liveweight gains in ruminants particularly those on medium or poor quality diets (Hussein and Jordan, 1991; Urbaniak, 1995; Galloway et al.; 1996; Walz et al., 1998), and can increase wool yields and efficiency of fiber production in sheep and goats

(Coatzee, 1995; Gregoire et al., 1996). Because of the need to maintain isonitrogenous diets, the FM ration was fed at a lower daily rate (76%). Although all supplements provided similar amounts of methionine, the smaller portion of pelleted ration in the FM diet resulted in a decrease of ration methionine. A reduction in the basal diet also provided less corn, a low ruminally-degraded protein source (Hussein and Jordan, 1991), which could account for some of the poor performance in the FM group. It is also possible that fishmeal products designed for use in cattle are not as effective in muskoxen due to significant differences in digestive process between the two species (Adamczewski et al., 1994b).

Within the experimental design, August represented peak fiber growth in measured values in all age classes. Although we did not measure rates of fiber growth in July, growth was observed to be rapid during this period also. By October, qiviut growth had slowed in all age classes, demonstrating a seasonal decline in fiber production. The lower qiviut growth rate in October temporally correlates with marked seasonal declines in forage quality and availability in natural muskox ranges (Jingfors, 1981). It also correlates with an endogenous decline in appetite in August, as deduced from changes in fasting metabolism (Lawler and White, 1997).

Although qiviut growth rate slowed considerably in October, continued growth was observed through November. No qiviut growth occurred between December 12 and April 1, as determined by dyebands placed on mid-sides of all animals in mid-December. These observations are broadly consistent with patterns of secondary follicle activity and

dormancy measured in captive muskoxen (Flood et al., 1989) and with wool growth patterns reported for mouflon rams (Lincoln, 1990).

Although the timing of qiviut synthesis coincides with peak and post-peak periods of protein intake, it is also occurring in conjunction with rapid growth in young animals and lactation in parturient females. The age-specific pattern of qiviut shed and timing of qiviut emergence thus may be reflecting changing physiological states and the animals' allocation of resources.

New qiviut growth was observed earliest in the post-parturient adult females, followed by adult steers and two year olds, and latest in the yearlings. Emergence proceeded opposite to documented shedding patterns, which occur earliest in yearlings and two year olds (late April to May), and latest in post-parturient females (late May to June) (Wilkinson, 1974; Groves, 1992). In this respect, muskoxen differ from cashmere goats and sheep, in which age-specific patterns of moulting are not readily apparent (C. Lupton, pers. comm.; Lincoln, 1990). However, in both wild and domestic breeds of sheep, seasonal increases in prolactin are closely associated with spring moult (Lincoln, 1990). In cashmere goats, administration of additional prolactin in early spring results in earlier moults, and prolactin inhibitors delay moulting (Dicks et al., 1994). Similar to wild sheep, serum prolactin levels in female muskoxen are nearly zero in winter with a steady increase in prolactin levels occurring from January to June. During pregnancy, prolactin concentrations are highest immediately prior to parturition (Tedesco, 1996). While pregnancy generally inhibits moulting, the parturient rise in prolactin may be

responsible for the rapid post-calving moult and early emergence of new qiviut in calving females.

In yearling muskoxen, higher rates of qiviut growth in August appear to compensate for later qiviut emergence. Seasonal increases in body mass, horn mass, and pelage of muskoxen occur from May to September, coinciding with periods of peak and post-peak plant productivity (White and Fancy, 1986; White et al., 1989; Flood et al., 1989; Adamczewski, 1992). Yearlings may exhibit seasonal partitioning of nitrogen for preferential investment in guard hair, body tissues, and replacement of body reserves during early and peak plant production. Qiviut growth may thus be partitioned to later in the summer, and then proceed at a comparatively rapid rate. Switching off summer protein synthesis in August (see Lawler and White, 1997), makes excess S-AAs available for rapid qiviut growth. Whether endogenously driven partitioning could be supported by feeding behavior is not known. However, Oakes et al. (1992) observed that yearlings in wild herds used proportionally more shrubs and forbs in spring and summer than adults, and that juveniles used higher ratios of *Salix* leaves to stems than adults. Differences in diet selection could potentially reflect different nutritional requirements for age-specific growth patterns, although an alternate explanation of juvenile diets could reflect their access to resources, dictated by lower dominance stature within social groups.

Experiment 2: Plane of Nutrition and Methionine Supplementation

Between-Year Effects

In Exp. 1, the efficacy of SMA supplements on qiviut growth was established within the span of a single wool growth season. However, because Exp. 2 took place over the course of two wool growth seasons (1996 and 1997), between-year effects cannot be overlooked.

Long term weather records for the Fairbanks area show that climatic conditions between years were quite similar, with the exception of an earlier green-up date in May 1997. Supplementation combined with earlier pasture growth may have played a role in uncharacteristically high rates of post-parturient live weight gain. However, calf body weights from weeks 1-10 did not differ between years with nutritional plane or SMA supplements, suggesting that milk production of dams was not influenced in early lactation. Between-year variation in brome grass growth in interior Alaska is positively correlated with precipitation from May to August (Laughlin and Restad, 1964; Klebesadel, 1998), and this did not deviate significantly from normal values, despite lower precipitation throughout 1997 (supplemented year). Differences in rates of qiviut production and greatest live weight gains were observed from August onwards, after grasses began to seed and senesce. Hence, results do not reflect different grazing conditions. However, the timing of the supplement effect may be associated with the seasonal decline in grazing quality as pasture grasses seed and senesce. Given the high

variability inherent to northern systems, the two years were similar for the climatic variables examined, resulting in comparable pasture conditions, with the exception of earlier green-up and grazing in May 1997.

Nutrient analyses indicate that hay quality at LARS was similar from May to late September in both years. However, from October through the completion of the annual qiviut growth cycle in 1997, LARS hay contained higher CP and lower ADF values than in 1996. No effects of late-season hay quality were observed in HP animals in 1997. Rates of HP qiviut growth did not differ between years after mid-September, and rates of post-calving live weight gain and hoof growth were similar. In LP animals, increased rates of qiviut growth that occurred after September 1997 could reflect greater levels of energy and protein from the higher quality hay in the final quarter of 1997. Analyses of between-year differences for pre-October : post-October ratios of live weight gain, hoof growth and measures of diameter along fibers failed to find an additive effect of hay, supporting the interpretation that increased LP performance in October resulted primarily from SMA supplements. After November 1, supplementation ceased, and the additional 2 mm of linear qiviut growth by LP cows from November through mid December of 1997 may have resulted from higher quality hay. Alternatively, additional growth could reflect a carry-over effect of supplements, which can continue for up to three months in merino sheep (Mata et al., 1995; 1997). Ultimately, late-season differences in rates of fiber growth in LP animals contributed little to staple length and total fleece yields as a result of significant declines in seasonal rates of wool growth at this time.

Qiviut characteristics and growth rates

Supplementing diets of lactating muskoxen with SMA increased raw fleece weights, rates of fiber growth, AFD, staple length and strength, irrespective of nutritional plane. Significant improvements in LWG and protein deposition were observed in the LP group only.

Provision of SMA increased raw fleece weights an average of 17% in HP and 24% in LP, which is within the range (6 to 29%) reported for SMA supplemented sheep (Staples et al., 1993). In sheep, greater wool yields with S-AAs result from increases in both fiber diameter and length (Reis, 1979; Russel, 1992; Reis and Sahlu, 1994). Recent studies also indicate S-AAs can stimulate fleece yields and AFD in angora goats (Sahlu and Fernandez, 1992; Sourì et al., 1998; Puchala et al., 1999), although fiber length may not be responsive to S-AA supplements (Reis and Sahlu, 1994). Qiviut production exhibits a similar pattern to sheep's wool, in that muskoxen fed SMA supplements produced qiviut with greater AFD and staple length.

A 76% increase in fiber strength reflects not only increased AFD, but also significant decreases in WFDV. The association of AFD, WFDV and fiber strength is well-studied in sheep where staple strength is influenced by variation in fiber diameter, both between and within fibers (McKinley et al., 1976; Reis, 1992). Thin areas along the length of fibers (high WFDV) can weaken them and contribute to breakage, leading to decreased fiber length and greater combing noilage in the processed product (Teasdale, 1985). Supplying adequate methionine to wool follicles improves fiber strength in sheep

(Reis, 1992), and appears to affect muskoxen in a similar manner. Qiviut fibers from supplemented animals also contained fewer regions that appeared “tender” or “splintered.”

Pickering and Reis (1993) and Mata et al. (1995, 1997) observed responses to RPMet supplements only when wool growth was well below potential. Similarly, Stephenson et al. (1991) and Cottle (1988) reported responses when sheep were fed at or below maintenance. This corresponds with the greater effects of SMA on wool qiviut production in LP muskoxen over the qiviut growth season. However, responses to methionine supplements were also observed in HP muskoxen. This result differs from most work with domestic sheep or goats, in which higher quality diets supplemented with RP Met do not result in improved performance (Baldwin et al., 1993; Gregoire et al., 1994; Purchas et al., 1998; Carneiro et al., 1998). In sheep and goats, lack of effect is often interpreted to indicate that methionine is not limiting to animal performance.

It is well established that lactation represents a high energy priority for females, such that lactating ewes and angora does tend to produce lower fiber yields than non-lactating females (Langlands, 1977; Masters and Mata, 1996; Sahlu, 1999). In lactating ewes, improved nutrition can result in higher wool production (Doney, 1964). Lactating muskoxen responded to RPMet with increased staple length, strength and AFD, similar to the response observed in supplemented lactating ewes by Floris et al. (1988), but in contrast to a study by Reis (1991) in which lactating ewes at pasture did not respond to methionine supplementation.

The restriction of the HP response to August and September, accompanied by peak LP responses in that period, suggests that methionine may be seasonally limiting for qiviut growth in lactating muskoxen. In female muskoxen, the period of qiviut growth and fattening extends through lactation, so that nutritional status is confounded with changes in physiological state associated with seasonal cycles. In both captive and wild lactating muskoxen, the majority of annual body weight gains occur from August to October (Thing et al., 1987; White et al., 1989; Adamczewski et al., 1992) during the annual rut. This period of compensatory gain in late summer and autumn coincides with significant declines in milk production (White et al., 1989; Parker et al., 1990), and appears to reflect a repartitioning of nutrients from milk synthesis to maternal body tissues (White et al., 1989; Adamczewski, 1992; White et al., 1997). Based on our findings, we would hypothesize that seasonal nutrient repartitioning results in increased competition for S-AAs between body mass gains, lactation and qiviut production in captive muskoxen.

In free-ranging domestic sheep, responses to methionine may be most pronounced in environments where there are large seasonal fluxes in feed supply (Pickering and Reis, 1993). Muskoxen experience a seasonal down-regulation in metabolic processes (White et al., 1984; Nilssen et al., 1994), which begins between August and September (Lawler and White, 1997) and broadly corresponds with declines in forage quality across historical muskox ranges (Jingfors, 1981). Decreases in metabolic rate are followed by lowered voluntary food intake (VFI), and slower rates of passage (ROP) (Holleman et al., 1984; White et al., 1984; Adamczewski et al., 1994a and b). These seasonally mediated

changes are considered part of a suite of adaptations that enable muskoxen to maintain body reserves in winter (Thing et al., 1987; Nilssen et al., 1994), but may also support qiviut growth and fattening in fall (White et al., 1997). Sahlu et al., (1999) suggest that decreasing VFI in lactating angora does restricts milk production, and thus increases availability of nutrients for mohair growth. Decreased VFI may have a similar effect in muskoxen. However, the association of lowered VFI with slower ROP and high gut fill also may be contributing to methionine limitation at this time. While increased food retention times, in combination with lowered metabolic rates may promote deposition of body reserves through efficient digestion of lower quality graminoid forage, slower ROP can simultaneously result in greater degradation of dietary protein by rumen microbes (Elimam and Ørskov, 1984), potentially limiting S-AAs entering the small intestine. If seasonal repartitioning of nutrients results in competition for S-AAs between lactation, body mass gains and qiviut growth, then methionine requirements for muskox females may not be met by captive diets in August and September. The fact that SMA supplementation improved fiber production in muskoxen on both nutritional planes, and enabled LP qiviut growth rates and fiber properties to approximate HP levels, clearly indicates the seasonal importance of methionine in qiviut production.

In unsupplemented animals, the lack of between-plane differences in mean raw fleece weight and rates of qiviut growth was unexpected and may be partly attributed to seasonal partitioning of nutrients. However, lack of differences also appears to reflect sample sizes. Power analyses indicate that additions of 1- 2 animals per group would have resulted in significant between-plane differences in fleece yields, AFD, and rates of

qiviut growth in August. Trends in unsupplemented muskoxen suggest a positive influence of dietary CP on qiviut production, resembling results reported for sheep (Aldden, 1979) and adult angora goats (Shahjalal et al., 1992; Sahlu et al., 1992; Jia et al., 1995). Furthermore, long term records at LARS show that HP females produce significantly greater raw qiviut yields than LP females. A tendency for unsupplemented HP animals to exhibit higher rates of fiber growth during August likely reflects a seasonal effect of dietary protein and increased S-AAs supplied by the HP pelleted ration.

Live weight and protein deposition

Between-plane differences in LWG have been documented previously for muskoxen in captivity (White et al., 1997) and on natural ranges (Oleson, 1994). White et al. (1989) noted a post-partum decline in body protein in lactating muskoxen, followed by a slow regain, and hypothesized that females may mobilize body protein for milk production if dietary protein is limiting, as reported in merino ewes (Lynch et al., 1991). The fact that SMA supplementation increased LWG and protein deposition (hoof growth) only in the LP group suggests that dietary methionine in HP diets may be preferentially partitioned to replenishment of body condition in lactating muskoxen. Sahlu et al. (1999) noted that nutrient demands are much greater for LWG and milk synthesis than for mohair production in lactating angora does, and consequently fiber growth appeared less sensitive to nutrient intake than LWG and milk production. Data from supplemented HP muskoxen support this observation, in that methionine was limiting for wool growth for

HP animals during August and September, but not for LWG or protein deposition at any point in the season. Supplemental RPMet can promote hoof growth in angora goats (Mengel et al., 1997), and LWG in sheep (Floris et al., 1988; Mata et al., 1992, 1995) and growing beef cattle (Klemesrud et al., 2000; Froidmont et al., 2000) when the post-ruminal supply of methionine is limiting. The fact that supplemented LP females exhibited similar rates of protein deposition and end of season LW to HP females indicates that S-AAAs were limiting for these processes. Generally, LP cows do not reach the same autumn LW as HP cows and conception may be delayed or skipped if body reserves are low during rut (White et al., 1997). A similar recovery of body reserves in the supplemented groups by October has important implications for annual reproduction and herd growth, since muskox fecundity is significantly linked to LW and body reserves in autumn (Adamczewski, 1992; White et al., 1997).

Ecological Implications

In sheep, it has been shown that condensed tannins (CT) in browse forage bind to plant proteins, and that moderate concentrations of CT can slow rates of ruminal degradation, increase absorption of S-AAAs in the duodenum and improve rates of wool growth (Wang et al., 1994; Barry and McNabb, 1999). Although diets of wild muskoxen are dominated by graminoids, willow browse is a primary component of summer diets (Thing et al., 1987; Klein, 1992). Actions of CT in browse forage of muskoxen could increase the supply of S-AAAs, supporting fiber growth. In a preliminary study with

captive muskoxen, increasing amounts of current annual growth of native willow (*Salix bebbiana*), fed as a supplement to hay and pelleted ration, were associated with increased qiviut length and feed intake (Boyd, 1993). Thus, summer browse may provide an important supply of bypass S-AAs to wild muskoxen during peak body growth, lactation and qiviut growth, which in turn may not be approximated by unsupplemented captive diets.

Captive muskoxen appear to have high methionine requirements during the wool (qiviut) growth season (May to November). Supplementing diets of growing and lactating muskoxen with rumen-protected methionine can increase qiviut yields and improve fiber length and strength, even for animals maintained on high quality diets. Rumen-protected methionine can effectively promote fiber production in captive muskoxen without increasing levels of protein in the diet.

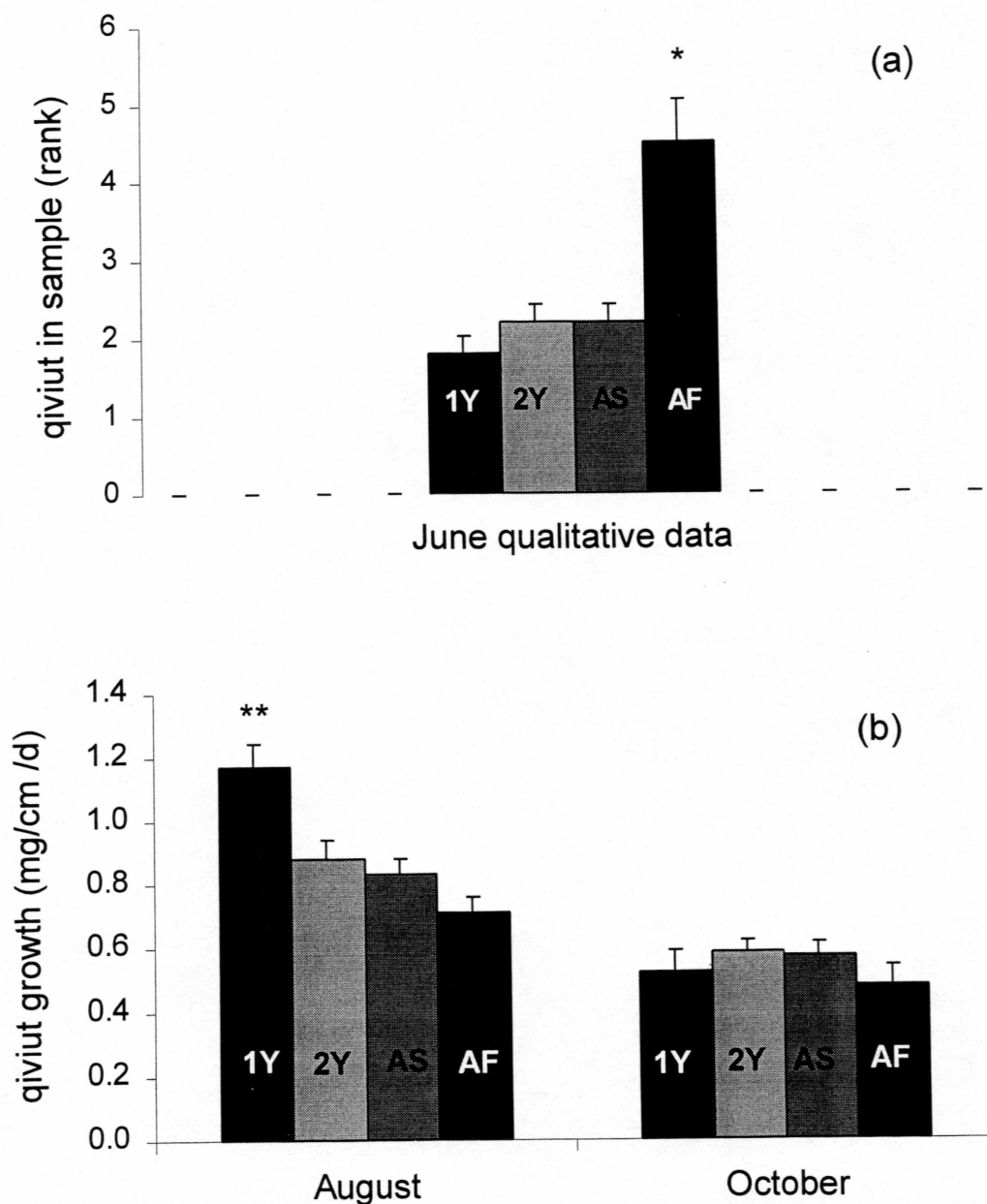


Figure 1. Seasonal patterns of qiviut growth from muskoxen in four age classes: 1Y = yearling (n=4); 2Y = 2 year-old (n=4); AS= adult steer (n=4); AF= lactating adult female (n=4).

(a) Rankings (1-6) of qiviut growth from 5x5 cm patches clipped in June. A rank of "1" corresponded to no qiviut in the sample, while a rank of "6" indicated levels of wool growth.

(b) Qiviut growth (mg/cm²/d) in August and October. Dietary treatments were pooled to show the age main effect. Regardless of dietary treatment, patterns of qiviut growth were consistent within age-classes.

* (P<.05) and ** (P<.01) reflect significant differences between age classes within month.

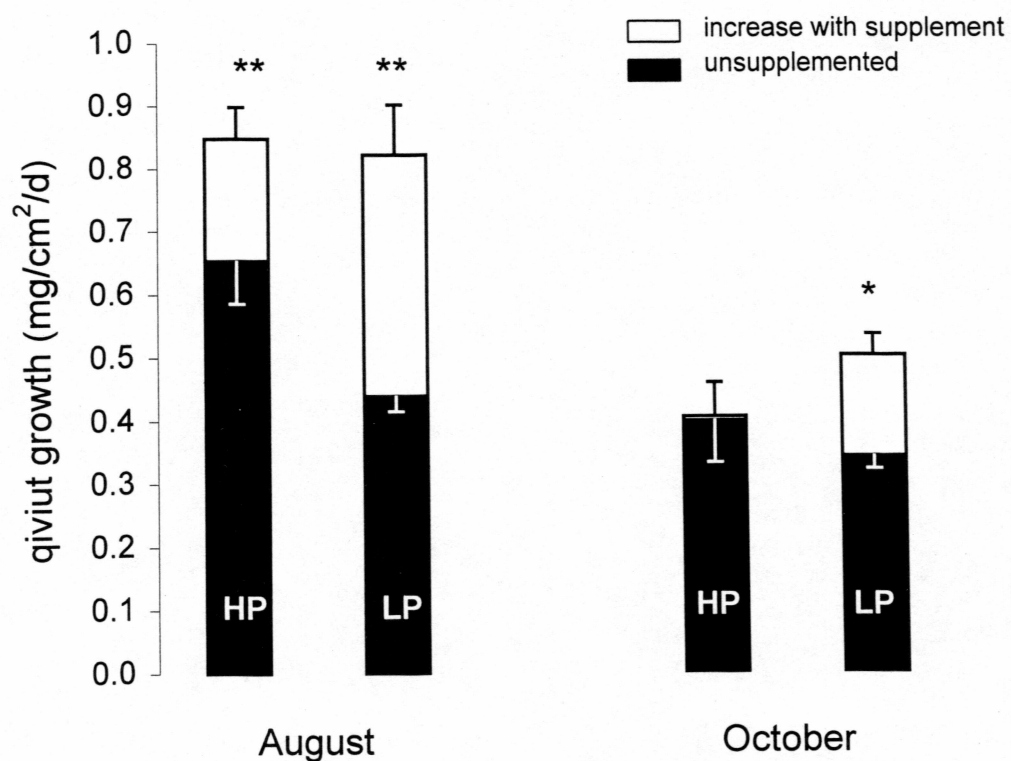


Figure 2. Qiviut growth from clipped patches (mg/cm²/d) in adult female muskoxen with and without methionine supplements provisioned from May through October. Dark columns show fiber growth without methionine and light columns demonstrate improvements with supplemental methionine. Throughout the course of the trial, females were divided into two nutritional groups, High Plane (HP; n=5) and Low Plane (LP; n=4) (White et al., 1989). * (P<.05) and ** (P<.01) indicate significant differences between the supplemented and unsupplemented qiviut growth within a nutritional plane.

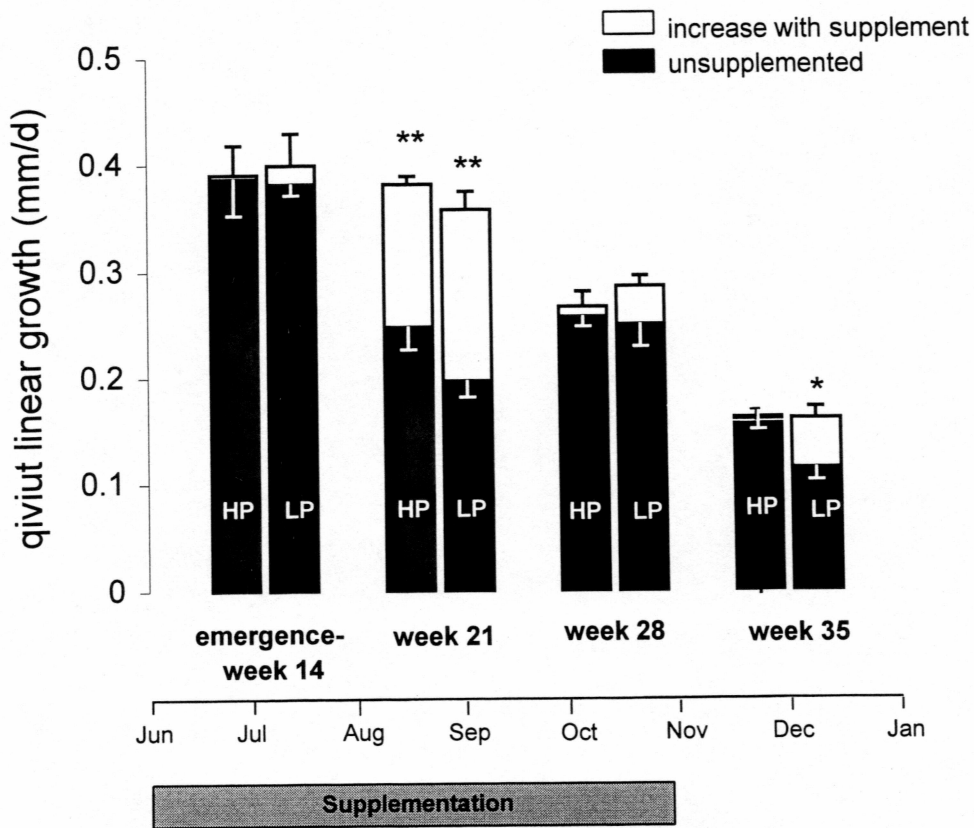


Figure 3. Linear growth rates of qiviut (mm/d) in adult female muskoxen with and without methionine supplements provisioned from May through October. Dark columns show fiber growth without methionine and light columns demonstrate improvements with supplemental methionine. Throughout the course of the trial, females were divided into two nutritional groups, High Plane (HP; n=5) and Low Plane (LP; n=4) (White et al., 1989). At week 35, the supplemented HP group grew .01 mm less qiviut than in the unsupplemented year, indicated by a white line on the bar. The second x axis and bar depict months of supplementation * (P<.05) and ** (P<.01) indicate significant

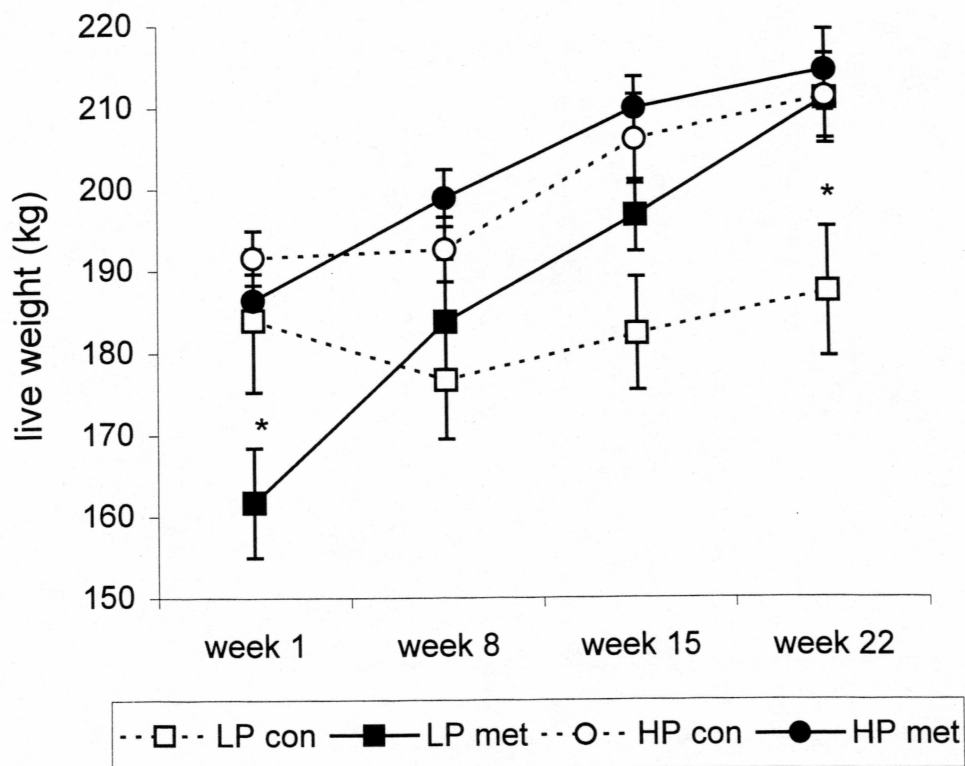


Figure 4. Post-calving live weight (kg) in adult female muskoxen with (met-solid line) and without (con-dashed line) methionine supplement provisioned from May through October. Throughout the course of the trial, females were divided into two nutritional groups, High Plane (HP; $n=5$) and Low Plane (LP; $n=4$) (White et al., 1989). Mean calving dates were 5/9, 5/9, 5/14 and 5/25 for HP con, HP met, LP con and LP met, respectively.

* indicates a significant ($P < 0.05$) difference between the supplemented and unsupplemented live weight within plane.

Table 1. Nutrient analysis (g/100g DM) of pelleted ration (University of Alaska's Textured Ration, Alaska Mill & Feed, Anchorage, AK) and brome hay harvested from Delta, AK

Item	Pelleted ration	Brome hay		
		1996	1997 (May-Sep)	1997 (Oct-Dec)
Crude protein	20.69	12.4	10.1	15.7
Crude fat	5.02	1.74	1.60	2.15
ADF	7.06	42.46	44.10	30.00
TDN	83.39	57.68	60.10	60.10
Ash	7.37	6.31	5.75	6.45
ME (Mcal/lb)	1.52	0.96	1.13	1.12

Table 2. Effects of methionine supplements on fleece weights and rates of qiviut growth for muskoxen maintained on four diets from May 21 to October 31

Trait ^a	Diet type				SEM
	Control	Smartamine	Mepron	Fishmeal	
Raw fleece wt, g/kg LW ^b	10.3	11.4**	11.0	10.6	.10
Qiviut growth, mg/cm ² /d					
August	.80	1.00*	.88	.91	.02
October	.43	.64*	.57	.52	.02
June clipped patch, rank ^c	3.0	2.7	2.8	2.3	.17

^a Each value is the mean from four muskoxen (one lactating adult female, one adult steer, one two-year old and one yearling)

* (P<.05) and ** (P<.01) indicate significant differences from control group, determined using Dunnett's *t* tests (2 sided).

^b Live weight on final date of experimental trial (October 31).

^c Analyzed with non-parametric statistics

Table 3. Means and standard errors for qiviut yield, fiber characteristics and hoof growth in adult female muskoxen with and without methionine supplements provisioned from May 1 to October 31

Trait	High Plane ^a		Low Plane ^a		SEM	Probability	
	No supplement	Supplement	No supplement	Supplement		Supplement main effect	Supplement x plane
No. of muskoxen	5	5	4	4			
Raw fleece wt, g/kg LW ^b	9.81	11.49**	9.28	10.52*	2.72	.004	.566
Raw fleece wt, kg	2.10	2.46 **	1.79	2.22 **	.136	.001	.617
Avge fiber diameter, μ m	15.39	16.39 *	14.59	16.11 *	.191	.000	.182
SD fiber diameter, μ m	4.18	4.35	4.44	4.40	.059	.535	.338
CV fiber diameter, %	27.16	26.52	30.43	27.33*	.308	.002	.016
Qiviut staple length, cm	4.4	5.0 **	4.0	5.1 **	.110	.000	.071
Staple strength, N/g	374	632 *	348	607 *	17.6	.000	.977
Within fiber variability, %	20.5	16.4 **	17.4	12.8 **	.874	.000	.652
June clipped patch, rank ^c	4.0	4.4	3.3	3.6	.268	.569	-
Hoof growth (mm/7d) ^d	1.45	1.56	1.07 ^e	1.56 **	.038	-	-

* (P<.05) and ** (P<.01) indicate significant differences **within** plane, determined in post-hoc tests.

^a Female muskoxen were maintained on either a high or low nutritional plane (White et al., 1989).

^b live weight on final date of experimental trial (October 31).

^c Analyzed with non-parametric statistics

^d Analyzed with independent samples *t* tests

^e Between plane differences (*t* < .05) in unsupplemented year.

Table 4. Precipitation, temperature, snowfall and green-up dates for Fairbanks, AK in 1996 and 1997.

Year	<u>Precipitation (cm)</u>			<u>Avg Temperature (°C)</u>			Snowfall in previous winter (cm)	Total days min T \geq 0° C ^a (April- May)	Green-up date ^b
	May-Jun	Jul-Aug	Sep-Oct	May-Jun	Jul-Aug	Sep-Oct			
1996	4.25	9.75	5.48	12.4	14.7	-2.4 ^d	140.3	23	5/12
1997	2.75	6.95	3.55	13.4	16.6	0.9	168.8	29	5/5
Normal ^c									
Mean	5.20	8.71	4.74	12.8	15.6	1.7	181.2	28	5/10
St.dev.	2.48	4.50	2.39	1.1	1.2	1.9	78.5	-	7d

^a Cumulative days from April 1 - May 31 in which minimum ambient temperature \geq 0° C

^b Greenup dates recorded by J. H. Anderson (in Thoman and Fathauer, 1998).

^c Normal based on long-term averages for precipitation, temperature and snowfall (29yr: 1968 to 1995), min temperature \geq 0° C (30yr:

1961 to 1990) (NWS, 1997); green-up date (21yr: 1974 to 1995) (Thoman and Fathauer, 1998).

^d Value > 1 SD from Normal.

Chapter 2.

Feeding rumen-protected methionine to improve qiviut yields from captive muskoxen²

Introduction

The production of super-fine fibers from ruminants is an important subsistence and commercial enterprise in rural communities and is a rapidly growing industry in western nations (Lupton, 1996). The newest of these fibers, qiviut, the fine underwool of muskoxen, is commercially important for processing by a subsistence cottage industry in Alaska (Bruce and Robertson, 1994). The Musk Ox Farm, located in Palmer, AK has pioneered the captive rearing of muskoxen for production of qiviut (Teal, 1958; Wilkinson and Teal, 1984). Instituted 30 years ago, the Musk Ox Farm is the largest and most successful commercial muskox facility in the world. Qiviut from this operation is commercially scoured and spun into yarn, and distributed to members of Oomingmak, an Alaska knitters' cooperative (Bruce and Robertson, 1994). Oomingmak's 200-plus members, distributed across 12 coastal villages, knit the qiviut yarn into various articles for sale. Improved qiviut production from the Musk Ox Farm would increase the amount of yarn available for this successful cottage industry.

² Prepared for submission to *Rangifer* as Robertson, M.A. , Rowell, J.E. and White, R.G. Feeding rumen-protected methionine to improve qiviut yields from captive muskoxen

Supplementing diets of sheep and angora goats with rumen-protected methionine (RPMet) can promote fiber yields and live weight gains (Russel, 1992; Sumner and Bigham, 1993; Reis and Sahlu, 1994), particularly if animals are fed at or below maintenance (Cottle, 1988; Stephenson et al., 1991; Mata et al., 1995). Through experimental trials at the Institute of Arctic Biology's Large Animal Research Station (LARS) at the University of Alaska Fairbanks, we have demonstrated similar responses to Smartamine M (SMA), a commercially available form of RPMet, when top-dressed onto the diets of captive muskoxen (Robertson et al., 1998; Robertson et al., in prep.). Of particular interest, we found methionine to be seasonally limiting for qiviut production even in animals receiving the highest quality diets. In these experimental trials SMA supplementation under carefully controlled feeding conditions resulted in significant increases in qiviut fleece weight (kg; g/kg LW), fiber growth rates from clipped patches (mg/cm²/d), and qiviut linear growth (mm/d).

At the Musk Ox Farm, animals inhabit outdoor pastures year-round and are fed communally. In communal feeding situations, individual food (and supplement) intake can vary according animal size, dominance, physiological status or individual preference (Fraser and Brown, 1990; Houpt, 1991). However, in a commercial setting, penning muskoxen individually to feed a ration top-dressed with supplement is not practical, and in order for a supplement to be effective it must be adaptable to existing management practices.

The aim of this study was to measure the response in raw qiviut fleece weights and live weight gains (LWG) to supplemental RPMet fed to muskoxen in a commercial setting.

Methods

The trial was conducted at the Musk Ox Farm, in Palmer, 65 km north-east of Anchorage, Alaska (61° 10' N, 149° 80' W). All experimental procedures were approved by the Animal Care and Use Committee at the University of Alaska, Fairbanks (protocol number 94-06).

Nine mature muskox steers (7 yr- plus) similar in liveweight and physiological status were paired by weight and age, and randomly assigned to two treatment groups: control (CON: n = 5) or Smartamine M (Rhone-Poulenc, Atlanta, GA) rumen-protected methionine supplement (SMA: n = 4). The two groups were maintained in adjacent pastures of similar size over the course of the experimental trial, which ran from May 7 to October 31, 1997. Two muskox bulls were included in each pen, resulting in similar stocking rates. Animals grazed seasonally available pasture, consisting of a smooth brome (*Bromus inermis*)/ Kentucky blue grass (*Poa pratensis*) mix, and had *ad libitum* access to brome hay offered in covered feeders (Groves, 1992). Three times weekly, muskoxen were group-fed a high protein pelleted ration (Mazuri® Muskox Diet, Purina Mills Inc.™, St. Louis, MO: Table 5) at a rate of 1.8 kg per animal. From May 7 through

October 31, 1997 all animals in the treatment pen received SMA top-dressed onto the pelleted ration at a rate of 9 g/animal along with approximately 18 g molasses used to bind SMA to the ration. Pelleted ration was placed in six wooden feed troughs that were spaced approximately 15 m apart, providing each animal adequate access to the ration. Muskoxen were free to move between feed troughs, and no attempt was made to discourage displacement behavior or to ensure that animals ate the supplement. During the first three weeks of the trial, feeding behavior, response to the supplement, and animal interactions were recorded by farm staff.

Muskoxen were weighed weekly, and qiviut was combed from animals the following spring by staff and volunteers at the Musk Ox Farm (White et al., 1991; Groves, 1992). Qiviut fleece weights were recorded on a per animal basis, and raw fleece weight refers to qiviut yield measured immediately after combing. Raw qiviut was subsequently batched for commercial scouring and processing, so clean fleece weights were not available. Data for one steer in the treatment group were dropped from analysis because of incomplete qiviut combing. Thus, final analysis was conducted on three SMA steers and five CON steers.

Data were analyzed using SPSS 7.0. Raw qiviut fleece weights from 1998 were compared using Student's *t* tests. A two-way repeated measures analysis of variance was used to test for differences in rates of live weight gain. Live weight (LW) was the dependent variable, the between-subject factor was treatment with two levels (CON, SMA), and the within-subject factor was week with four levels (Week 6, 12, 18, 24). To assess between-group and between-year variability in qiviut production, a two-way

repeated measures analysis of variance was used to test for differences in raw qiviut fleece weights (kg) and fleece weights corrected for live weight (g/kg LW) over two consecutive years. Raw fleece weight was the dependent variable, while treatment (CON, SMA) and year (1997, 1998) were the between and within subject factors, respectively. The two years of qiviut production following the institution of Mazuri® pelleted ration in 1996 were 1997 and 1998. Only fleece weights from animals that were completely combed according to facility combing records were used in the analysis. Two animals were not combed completely in 1997, and these data points were estimated using average raw fleece weight from 1994 to 1996.

Results

Performance data from the 1998 qiviut harvest are shown in Table 6, along with data from 1997, the year before supplementation. In analysis of the 1998 data, raw qiviut fleece weights (kg) tended to be greater in animals that received SMA supplements than in controls ($p = 0.06$; Figure 5). In 1998, fleece weight corrected for LW at the time of combing (g/kg LW) was lower in the CON group, but differences were not significant ($p = 0.39$; Figure 5). Rates of LWG from May 7 to October 31, 1997, the year of supplemental feeding, did not differ between groups over the course of the trial ($F = 0.30$, $p = 0.60$; Figure 6).

Prior to supplementation, average fleece weights ($\text{kg} \pm \text{SE}$) were similar between the two groups (Fig. 7a, pre-treatment year), as were fleece weights corrected for LW

(g/kg LW) (Fig 7b, pre-treatment year). Repeated measures analysis of variance for 1997 and 1998 qiviut fleece weights indicated no between-group differences (kg: $F = 0.06$, $p = 0.18$; g/kg LW: $F = 0.16$, $p = 0.66$). A significant main effect of year (kg: $F = 11.28$, $p = 0.02$; g/kg LW: $F = 10.26$, $p = 0.02$) reflected increased fleece weights for both groups in 1998 (Figure 7). Post-hoc tests showed that raw fleece weights increased significantly from 1997 to 1998 in the treatment group (kg and g/kg LW: $p < 0.05$) but not in the control group ($p > 0.05$). The interaction of year and treatment was not significant (kg: $F = 1.38$, $p = 0.29$; g/kg LW: $F = 2.13$, $p = 0.20$).

Discussion

Mature muskox steers maintained in a commercial setting produced marginally greater qiviut yields when provisioned with SMA supplements, while LWG remained unchanged. After 6 months of supplementation, average raw fleece weight (kg) in the SMA group was 11% greater than CON. Due to the low sample size of the treatment group ($n = 3$), and the lack of significance when corrected for LW, results are considered preliminary. However, significant increases in fleece yields from 1997 to 1998 for the treatment group only, both in raw yields (kg) and yields corrected for LW (g/kg LW), support the effect of SMA on fleece production, independent of between-year or between-group differences.

In experimental trials at LARS (Robertson et al., in prep.), we determined that SMA supplements were palatable to muskoxen, and, similarly, field notes from the Musk Ox Farm indicate that muskoxen acclimated rapidly to SMA in the diet. Displacement behavior occurred regularly during feeding, and sub-dominant animals sometimes had limited access to the pelleted ration. Adhesion of the top-dressed supplement to the dry pelleted ration was only partially accomplished with molasses, and approximately 1 to 2 g of SMA remained in each trough after pelleted rations were consumed. Therefore, it appears that not all animals received the same SMA intake in this commercial setting. Even given these constraints, supplementation produced a measurable effect on qiviut yield in mature steers.

Our finding of a positive influence of SMA on raw fleece weight with no effect on LWG is similar to previous results reported for muskoxen on high quality diets (Robertson et al., in prep.). In experimental trials at LARS, we showed that SMA supplementation increased qiviut yields in growing and lactating muskoxen on high planes of nutrition. However, increased rates of LWG occurred only in lactating females on a low plane of nutrition. In animals maintained on high plane of nutrition, seasonal repartitioning of nutrients appeared to result in preferential use of dietary methionine for replenishment of body reserves, such that rates of qiviut growth were significantly improved with SMA supplements while rates of liveweight gain were not affected. Positive responses in fiber growth to SMA supplements at the Musk Ox Farm, without changes in LWG, suggest a similar mechanism may limit rates of qiviut growth in mature steers, even when animals are maintained on very high quality diets. Providing RPMet

can thus promote qiviut production in captive muskoxen without increasing levels of protein in the diet.

Responses in raw fleece weight were lower for SMA supplemented steers at the Musk Ox Farm than for lactating females (17%) or yearlings (15%) at LARS. Similarly, an array of RPMet supplements had the least effect on qiviut fleece yields from adult castrates at LARS (Figure 8). Since mature steers have reached maximum size and live weight, and do not undergo the seasonal weight loss of rutting activity, they would have lower energy and protein demands through the summer than reproductively active males, growing animals or lactating females. As demonstrated experimentally, sex, age and reproductive status can influence the efficacy of RPMet supplements in muskoxen (Robertson et al., in prep.). Animals fed poorer diets or those with greatest seasonal energy and protein requirements, such as growth or lactation made the most gains with RPMet. In sheep, it has long been known that growing lambs and lactating ewes have higher protein requirements than mature dry ewes (Ensminger, 1952). Competing demands for body protein deposition and milk synthesis boost requirements for methionine, and subsequently methionine is more likely to be limiting in high-producing animals (Storm and Ørskov, 1984). Adding RPMet to diets adequate in protein can promote fiber production only if post-ruminal supply of methionine is limiting (Klemesrud et al., 2000). Results at the Musk Ox Farm are preliminary, but suggest that methionine was rate-limiting to qiviut growth in steers, although to a predictably lesser degree than previously observed in growing or lactating animals. Experimental results strongly indicate that even high quality diets are limiting in methionine for growing and

lactating captive muskoxen (Robertson et al., in prep.), and thus RPMet supplementation is recommended for maximal qiviut production in these groups.

Differences in basal diet can also contribute to the effectiveness of RPMet supplements (Cottle, 1988; Reis, 1988; Pickering and Reis, 1993). The pelleted ration used at the Musk Ox Farm differs from the ration fed at LARS (University of Alaska's Textured Ration, Alaska Mill & Feed, Anchorage AK; White et al., 1989; Robertson et al., in prep.). Additionally, rates of pasture growth and seasonal availability of pasture can vary with latitude and climate (Van Soest, 1982). Extended availability and quality of pasture in Palmer, AK (Klebesadel, 1998), when compared to LARS (64° 49' N, 147° 43' W) could result in seasonally higher rates of qiviut growth in late summer and fall, when methionine was determined to be limiting in lactating animals at LARS.

Fleece weight was used to gauge the effectiveness of the supplement because it did not interfere with regular commercial processes. Because of combing variability between years and animals (Figure 9), a much larger sample size would be needed to detect significant treatment effects using this variable alone. Although raw fleece weights allow a preliminary assessment, using indices of qiviut growth rate, such as clipped patches or dyebanding (Chapman and Wheeler, 1963; Robertson et al., in prep.) can provide more sensitive standard measures, demonstrate seasonality of supplement effects, and offer insight into requirements of different age and reproductive classes. Such measures are particularly useful to large commercial facilities, because they avoid sampling error inherent to annual fleece harvests involving multiple combers with different levels of experience. We further encourage the use of objective measures to

assess commercially important fiber qualities, such as average fiber diameter, fiber length and fiber strength (Lupton, 1987; Rowell et al., 1999).

The cost of feeding SMA supplement for 180 days is low (\$10.00/animal) when the high market value of qiviut is considered (\$330/kg), so that the initial investment can be recouped with minimal increases in fiber yield. Nonetheless, while SMA tended to improve qiviut yields, administration of top-dressed supplements was labor-intensive and could prove inefficient in large-scale muskox production. Ideally, RPMet supplements for qiviut production should be pelleted into the ration. Further investigation into incorporation of RPMet supplements into a pelleted ration is recommended, as pelleting Smartamine M into a ration is against manufacturer recommendations because the process can damage the protective coat, resulting in ruminal degradation of methionine. Alimet®, a methionine hydroxy analog, is a form of ruminal bypass methionine that can be pelleted into feed, and demonstrates a ruminal clearance rate of approximately 40% in dairy cattle (Robey and Fitzpatrick, 1996). Fishmeal (FM) is another feed supplement that is high in methionine, is naturally resistant to ruminal degradation and can withstand pelleting (Hussein and Jordan, 1991). Although we did not observe significant effects of FM on qiviut yields in LARS experimental trials (Robertson et al., in prep.), positive effects of FM on N balance and fiber yields in sheep and goats suggest that its potential for use in muskox diets should not be discounted. Alternatively, amino-acid chelates can be used to prevent degradation of amino acids in the rumen, and improved fiber yields have recently been reported for angora goats fed Zn-methionine supplements (Purchas et al., 1999). Finally, sulfur enrichment of pasture also can improve wool yields in

domestic sheep, in part by increasing rates of bacterial protein synthesis (Kennedy and Siebert, 1971; Qi and Lupton, 1994). The feasibility and cost of improving post-ruminal protein supplies through sulfur-enriched pasture or grass hay should also be explored.

Positive effects of RPMet on qiviut yields in both experimental and commercial settings, combined with the high value of muskox underwool, indicates that RPMet is a practical and economical way to boost qiviut production in captive muskoxen, although efficient methods of supplement delivery need to be addressed. Increases in individual animal productivity, in turn, can provide more raw product to help meet the demands of the Oomingmak knitters' Cooperative.

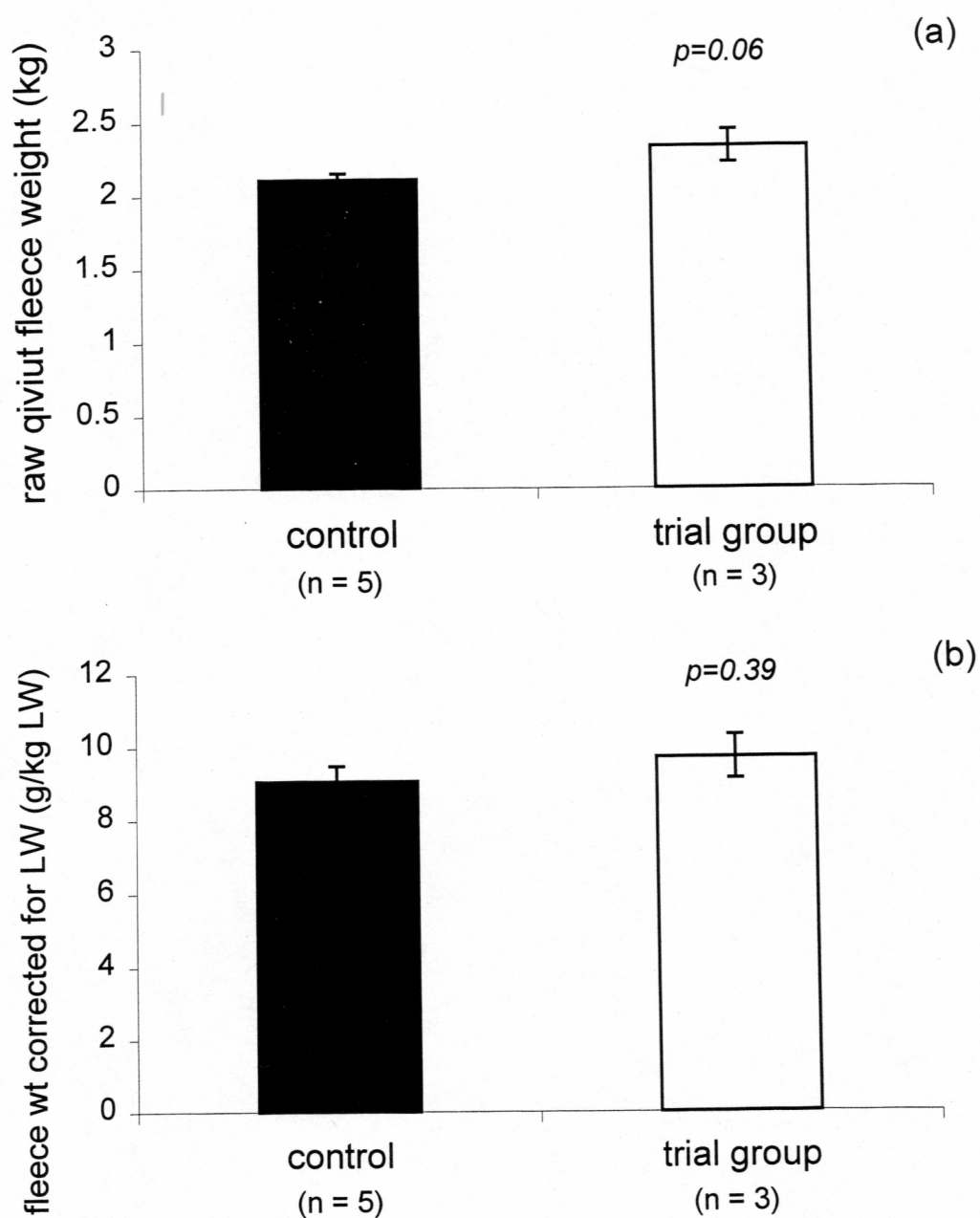


Figure 5. Qiviut fleece weights in 1998 from adult muskox steers at the Musk Ox Farm in Palmer, AK. Data are expressed (a) in absolute yields (kg) and (b) corrected for live weight (g/kg LW). Dark bars (n=5) show fleece weight for controls, and light bars (n=3) show fleece weights for animals provisioned methionine supplements provided from May to October 1997. Qiviut fleece weights represent fiber growth from the previous year (May to October, 1997). Qiviut was combed from animals following natural shedding in spring of 1998. Qiviut fleece weights from control and trial group were compared using Student's *t* tests.

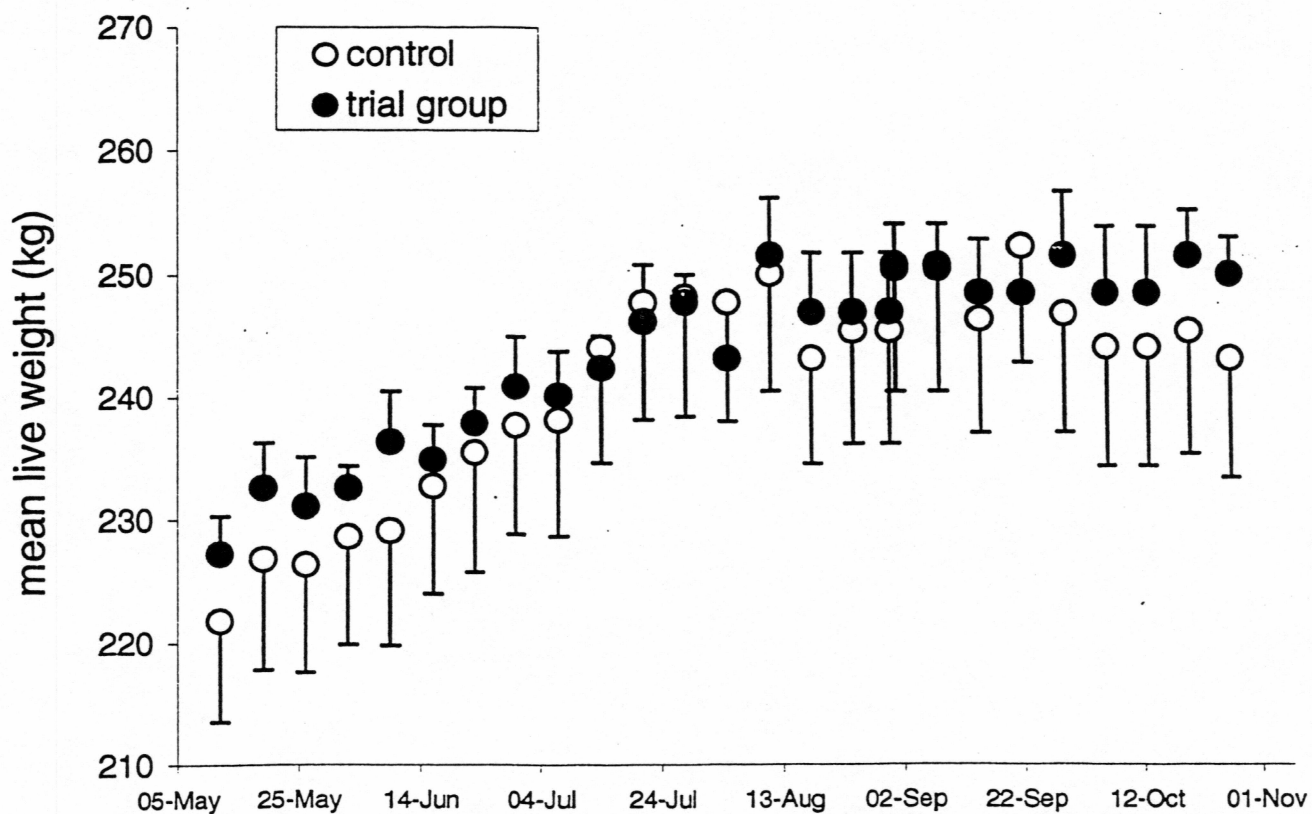


Figure 6. Live weights (kg) in adult muskox steers with (closed circles; $n=3$) and without (open circles; $n=5$) methionine supplements provisioned between May 7 and October 31, 1997.

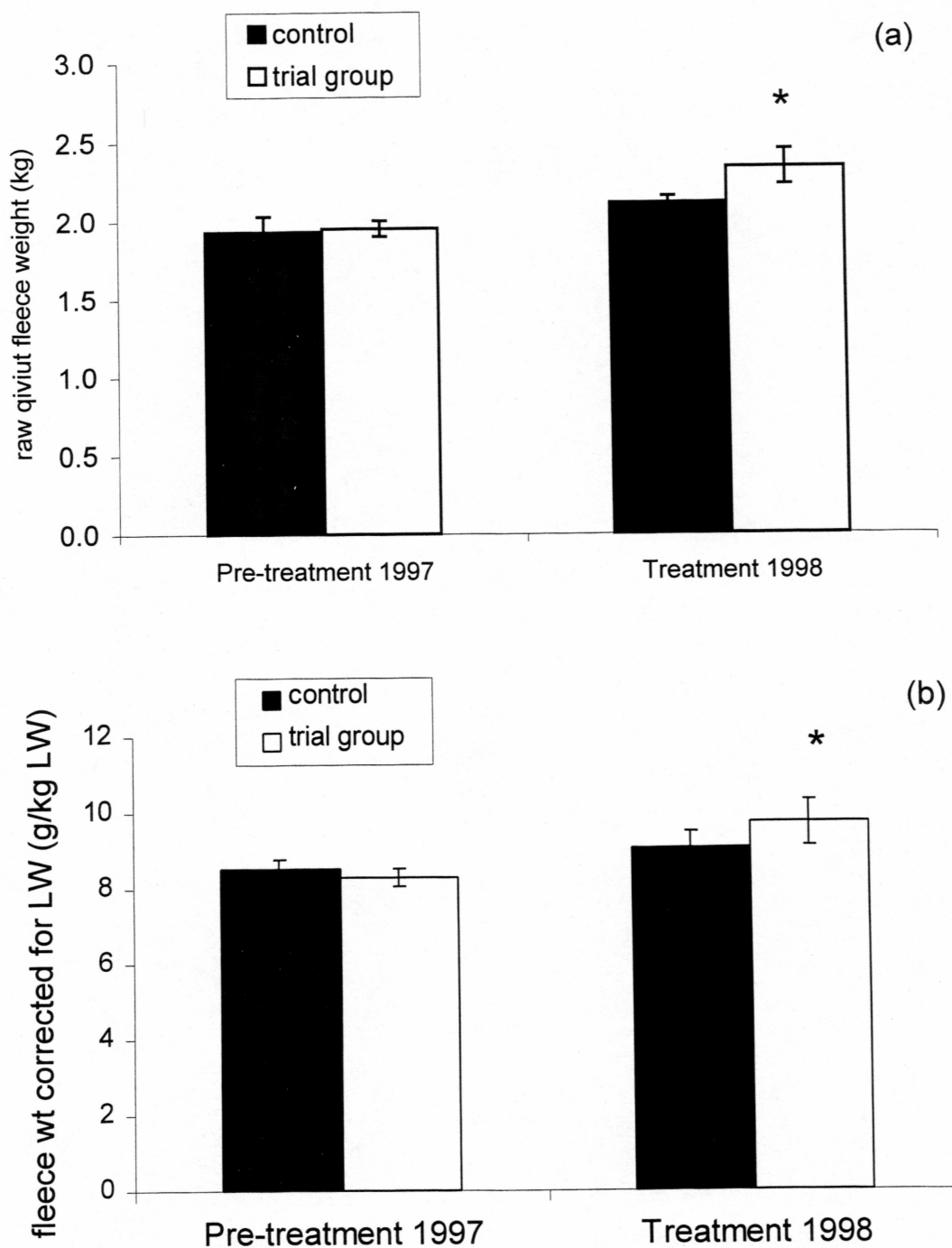


Figure 7. Qiviut fleece weights in 1997 (pre-treatment year) and 1998 (treatment year) for adult muskox steers with (light bars; $n=3$) and without (dark bars; $n=5$) methionine supplements provided from May to October 1997. Fleece weights are presented (a) as absolute yields (kg) and (b) corrected for live weight (g/kg LW). * ($P<.05$) indicates significant between year differences within trial group between 1997 and 1998 based on repeated measures ANOVA post-hoc tests.

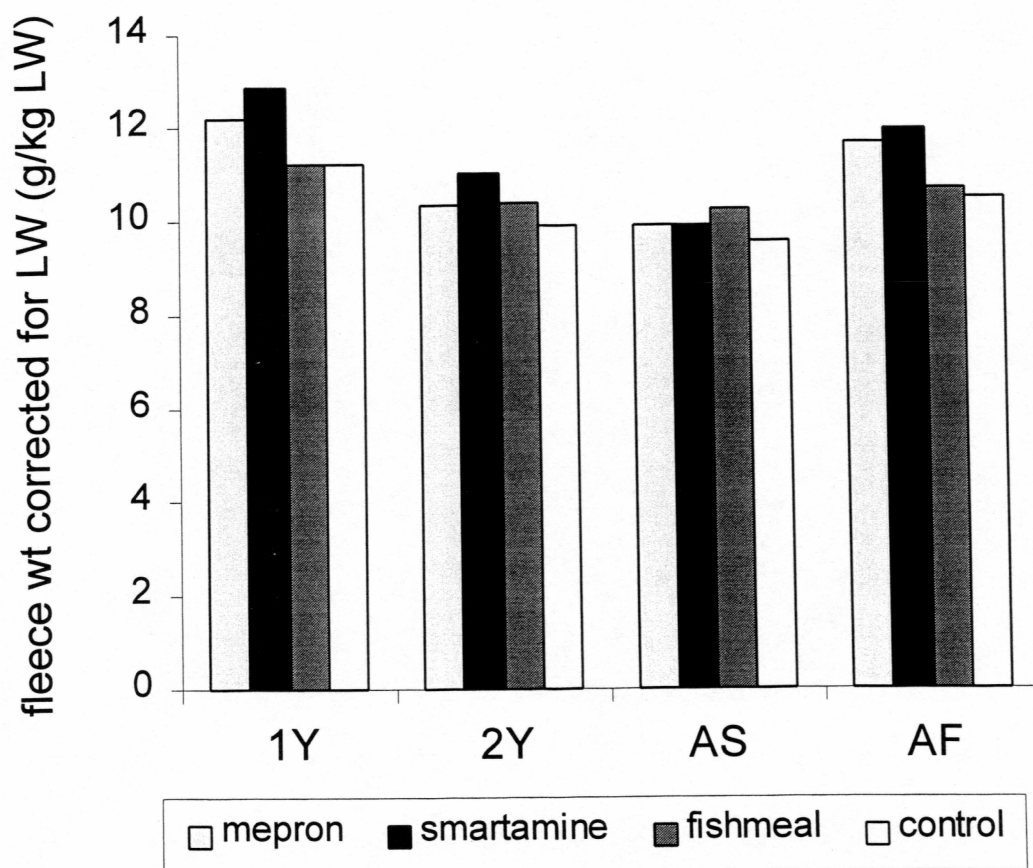


Figure 8. Qiviut fleece weights corrected for live weight (g/kg LW) from LARS muskoxen in four age classes: 1Y = yearling; 2Y = 2 year-old; AS = adult steer; AF= lactating adult female. Animals were provisioned with one of four dietary treatments (Mepron, Smartamine, fishmeal, control) from May 21- Oct 31, 1996 (Robertson et al., in prep.).

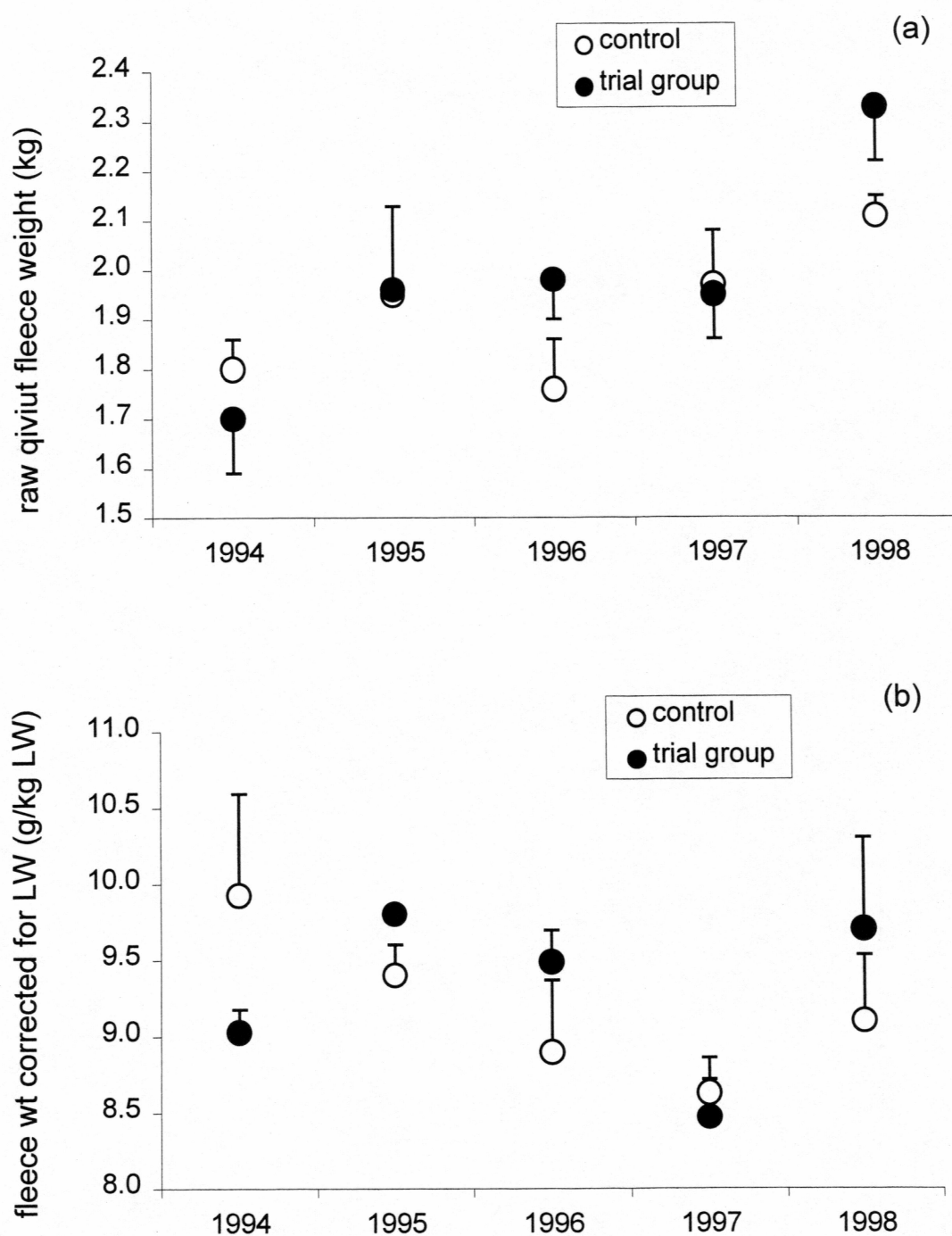


Figure 9. Qiviut fleece weights (a) in absolute yields (kg) and (b) corrected for live weight (g/kg LW) for adult steers from 1994 to 1998 at the Musk Ox Farm. Trial group (open circles) were provisioned with methionine supplements from May to October 1997, while control group (closed circles) received no supplement. Only animals that were combed completely are presented. Within year sample sizes follow: trial group: 1994, 97 n=2; 1995 n=1; 1996, 98 n= 3; control: 1994, 97 n=4; 1995 n=2; 1993, 96, 98 n=5.

Table 5. Approximate chemical composition¹ (g/100g DM) of pelleted ration (Mazuri® Musk Ox Diet, Purina™ Mills Inc., St. Louis, MO)

Item	Pelleted ration
Crude protein	17.7
Crude fat	3.1
Crude fiber	13.0
NDF	31.1
ADF	16.4
Nitrogen-Free Extract	48.0
Ash	8.2

¹ Based on ingredient analysis published by Mazuri® Company on 2/11/97. Further information available at <http://www.Mazuri.com>. Accessed March 5, 2000.

Table 6. Live weights and qiviut fleece weights for adult steers at the Musk Ox Farm in 1997 and 1998, preceding and following supplementation with rumen-protected methionine

Animal	ID #	Live weight (kg) ^a		Qiviut fleece wt.			
				(kg)		(g/kg LW)	
		1997 ^b	1998	1997 ^b	1998	1997 ^b	1998
No supplement							
Rodeo	305	195	200	1.73	2.09	8.84	10.45
Maurice	325	227	234	1.95	2.05	8.60	8.76
Eluk	352	218	241	1.77 ^d	2.27	8.13 ^d	9.42
Midnight	341	250	243	2.27	2.09	9.09	8.49
Ernie	361	238	255	1.91	2.05	8.00	8.05
mean		226	235	1.93	2.11	8.53	9.06
SE		9	21	.10	.04	.21	.43
Supplement ^c							
Louie	323	234	234	2.05	2.55	8.74	10.89
Esther	337	245	239	1.95 ^e	2.18	7.96 ^e	9.14
Chilkoot	377	227	250	1.86	2.27	8.20	9.08
mean		236	241	1.95	2.33*	8.30	9.70*
SE		5	5	.05	.11	.23	.60

^a Live weight at date of combing.

^b Year prior to initiating supplemental SMA trial.

^c SMA supplement provided at rate of 9g/animal in 1997. LW and fleece wt in 1998 reflect effects of supplement.

^d Interpolated value based on average qiviut yield from 1994-96.

^e Interpolated value based on average qiviut yield from 1994 and 1996 (1995 comb incomplete).

* (P<.05) indicates significant between year differences **within** treatment group between 1997 and 1998 based on repeated measures ANOVA post-hoc tests.

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Appendix A-1. Qiviut growth in August and October

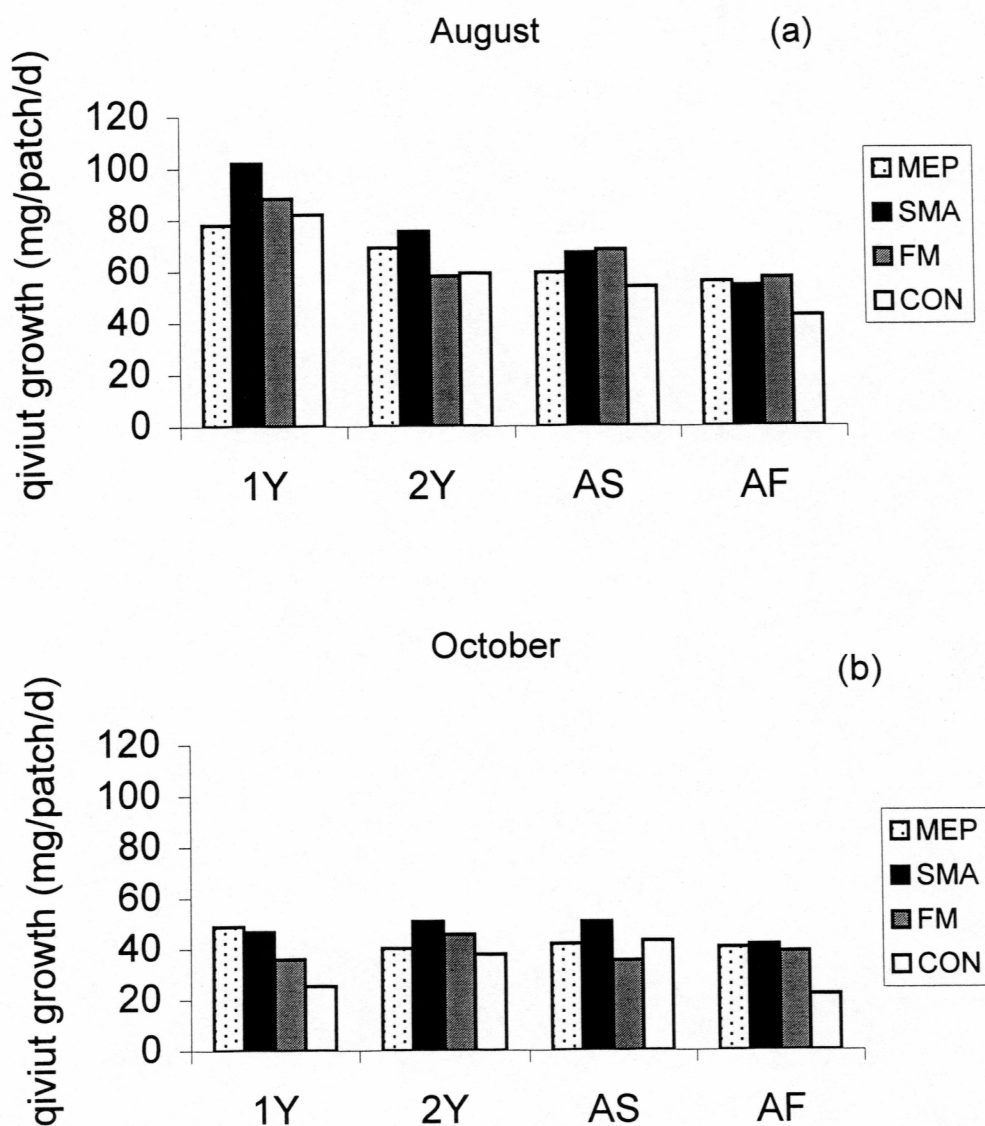


Figure 10. Qiviut growth (a) in August and (b) in October, measured by clipping 5x5 cm patches in four age classes of LARS muskoxen: 1Y = yearling; 2Y = 2 year-old; AS = adult steer; AF= lactating adult female. Animals were provisioned with one of four dietary treatments (Mepron, Smartamine, fishmeal, control) from May 21- Oct 31, 1996 (Robertson et al., in prep.).

Appendix A-2. Mean diameter along qiviut fibers

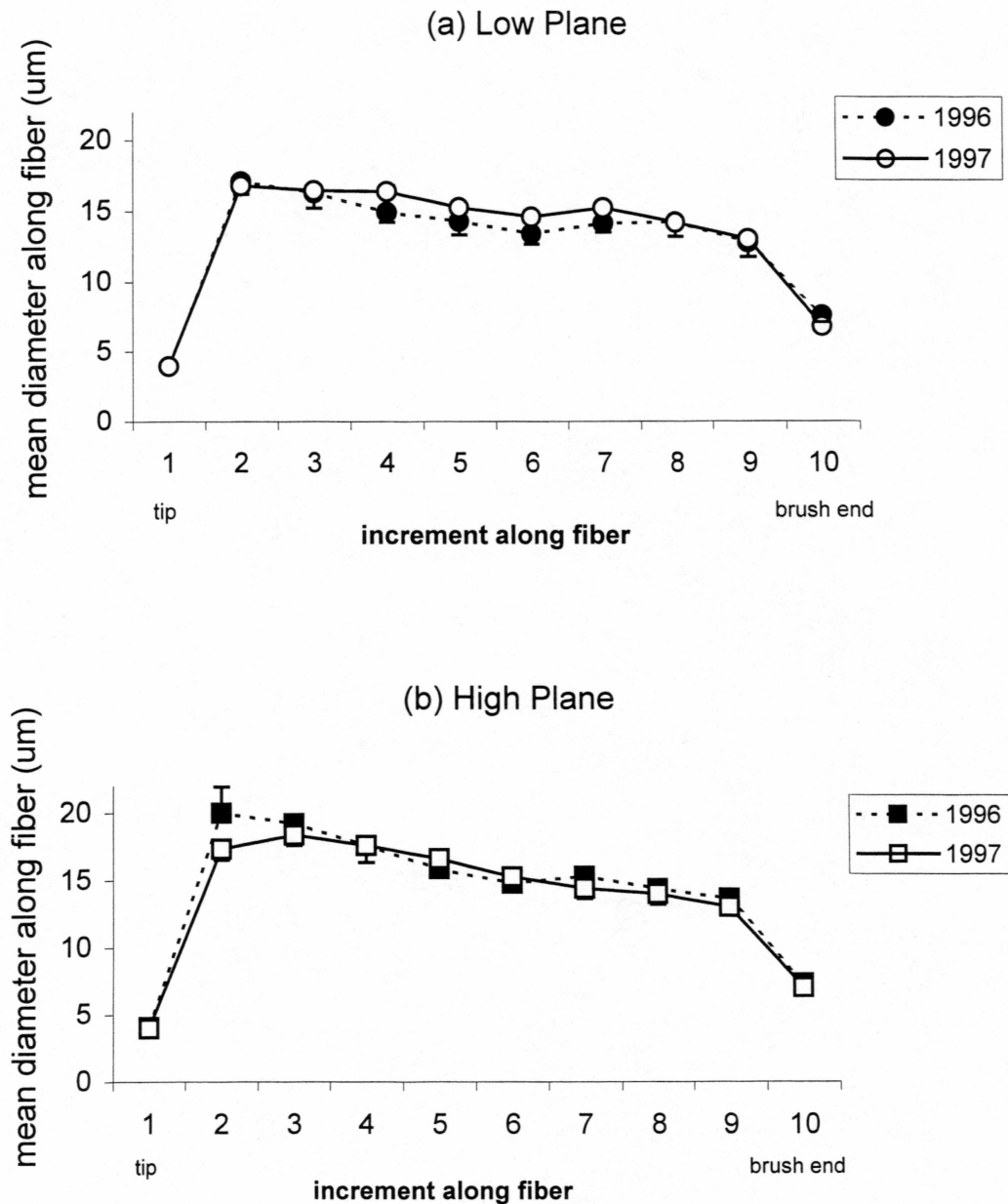


Figure 11. Mean fiber diameter along individual qiviut fibers from female muskoxen without (1996-dashed line) and with (1997-solid line) methionine supplements between May and October. Throughout the course of the trial, females were divided into two nutritional groups, Low Plane (a) ($n=4$) and High Plane (b) ($n=5$) (White et al., 1989) 10 qiviut fibers per animal were used to calculate average diameter at 10 evenly spaced intervals along fibers.

Appendix A-3. Live weight of muskox calves from birth to 10 weeks

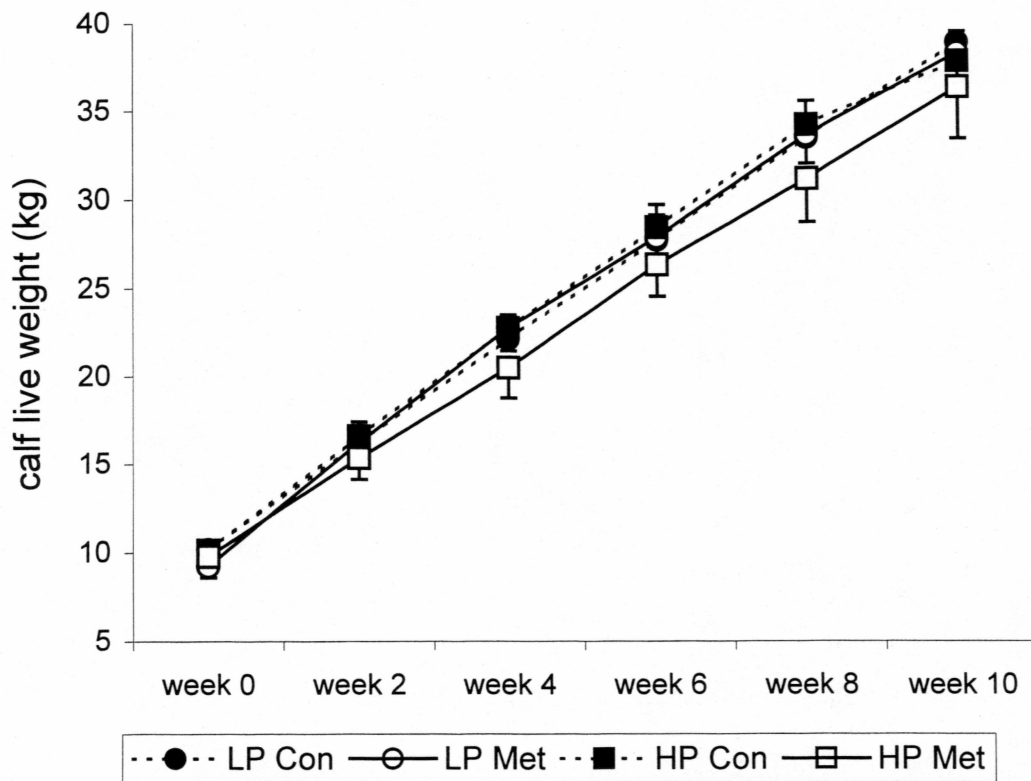


Figure 12. Average live weight (kg) of muskox calves from birth to 10 weeks (HP n=4; LP n=3) born to adult female muskoxen provided methionine supplements (solid line) or no supplements (dashed line) between May and October. Throughout the course of the trial, females were divided into two nutritional groups, High Plane (HP) and Low Plane (LP) (White et al, 1989). Mean calving dates were 5/9, 5/9, 5/14 and 5/25 for HPCon, HPMet, LPCon and LPMet, respectively.

Appendix A-4. Mechanical measures of qiviut yield and fiber diameter

Table 7. Calculated qiviut yield and mean fiber diameter for shoulder, mid-side and rump areas of female muskoxen with and without methionine supplements provided from May 1 to October 31 (SE values in parentheses)
(High plane $n = 5$, Low plane $n = 4$)

SHOULDER SAMPLES

Treatment	Calculated qiviut yield, %		Mean fiber diameter (um)		SD fiber diameter (um)	
	High plane	Low plane	High plane	Low plane	High plane	Low plane
No supplement	83.71 (3.40)	73.66 ^c (1.70)	15.39 (0.28)	14.59 (0.44)	4.18	4.44
Supplement	80.73 (2.76)	80.22 ^b (.73)	16.39 ^b (0.17)	16.11 ^b (0.30)	4.35 ^b	4.40

SIDE SAMPLES

Treatment	Calculated qiviut yield, %		Mean fiber diameter (um)		SD fiber diameter (um)	
	High plane	Low plane	High plane	Low plane	High plane	Low plane
No supplement	83.17 (2.37)	71.88 ^a (2.45)	14.83 (0.22)	14.44 (0.32)	3.97	4.33
Supplement	83.11 (1.40)	83.28 ^b (1.63)	15.26 (0.29)	15.52 (0.20)	3.99	4.11

RUMP SAMPLES

Treatment	Calculated qiviut yield, %		Mean fiber diameter (um)		SD fiber diameter (um)	
	High plane	Low plane	High plane	Low plane	High plane	Low plane
No supplement	84.69 (1.87)	72.01 ^a (3.97)	14.53 (0.26)	14.15 (0.53)	3.99	4.27
Supplement	81.53 (3.31)	81.44 (1.74)	15.42 ^b (0.26)	15.28 (0.23)	4.05	4.19

^a significantly different between planes ($U < .05$)

^b significantly different within plane (supplemented vs non-supplemented) ($P < .05$)

^c difference between HP and LP calculated qiviut yield approaches significance ($U < .10$)